IBRACON 2008
50^0 Congresso Brasileiro do Concreto
September 5, 2008

RECENT ADVANCES IN CONCRETE AND APPLICATION OF NANOTECHNOLOGY

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Congratulations to the Brazilian Concrete Congress on the 50th Session

Contributing Researchers

- Liberato Ferrara, Politecnico di Milano
- Raissa Ferron, Northwestern University
- Amedeo Gregori, University of L'Aquila
- Seung Hee Kwon, Northwestern University
- Jean-Juste Mbele, Schlaumberger
- Paramita Mondal, Northwestern University
- Yon-Dong Park, Daegu Haany University
- Zhihui Sun, University of Louisville
- Nathan Tregger, Northwestern University
- Thomas Voigt, USG

High Strength Concrete

Maximizing compressive strength

Burj Dubai
"Dubai Tower"
> 800 m (1/2 mile)
[courtesy of wikipedia.org]

High Performance Concrete

Maximizing durability

Fresh State Properties

Flowability, compactibility

Presentation Roadmap

SCC

- Mix design model
- Segregation (Fiber)
- Formwork Pressure
- Structural Buildup
- Slip-Form Paving
- From lab to practice

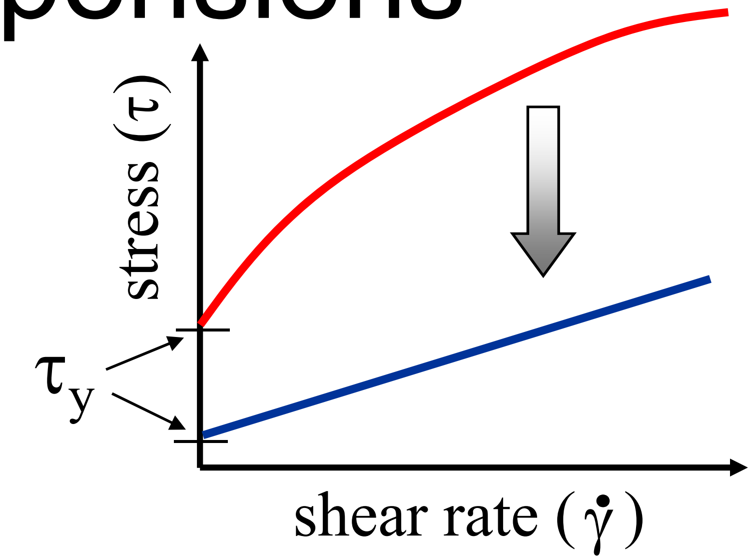
Nanotechnology

Self-Consolidating Concrete

- Movie:

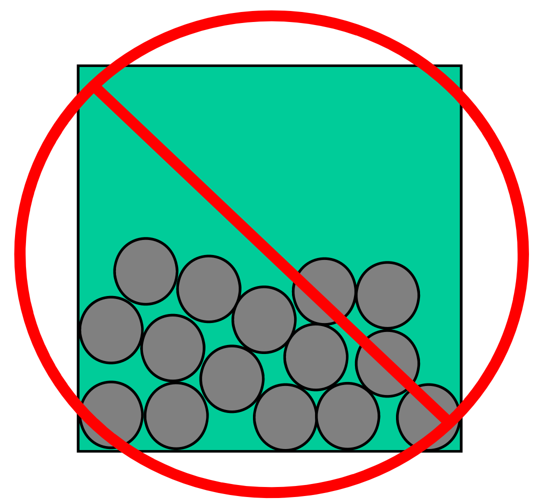
Conditions for Self-Flowing Suspensions

- Low stress required to initiate flow:
  ⇨low yield stress (τ_y)

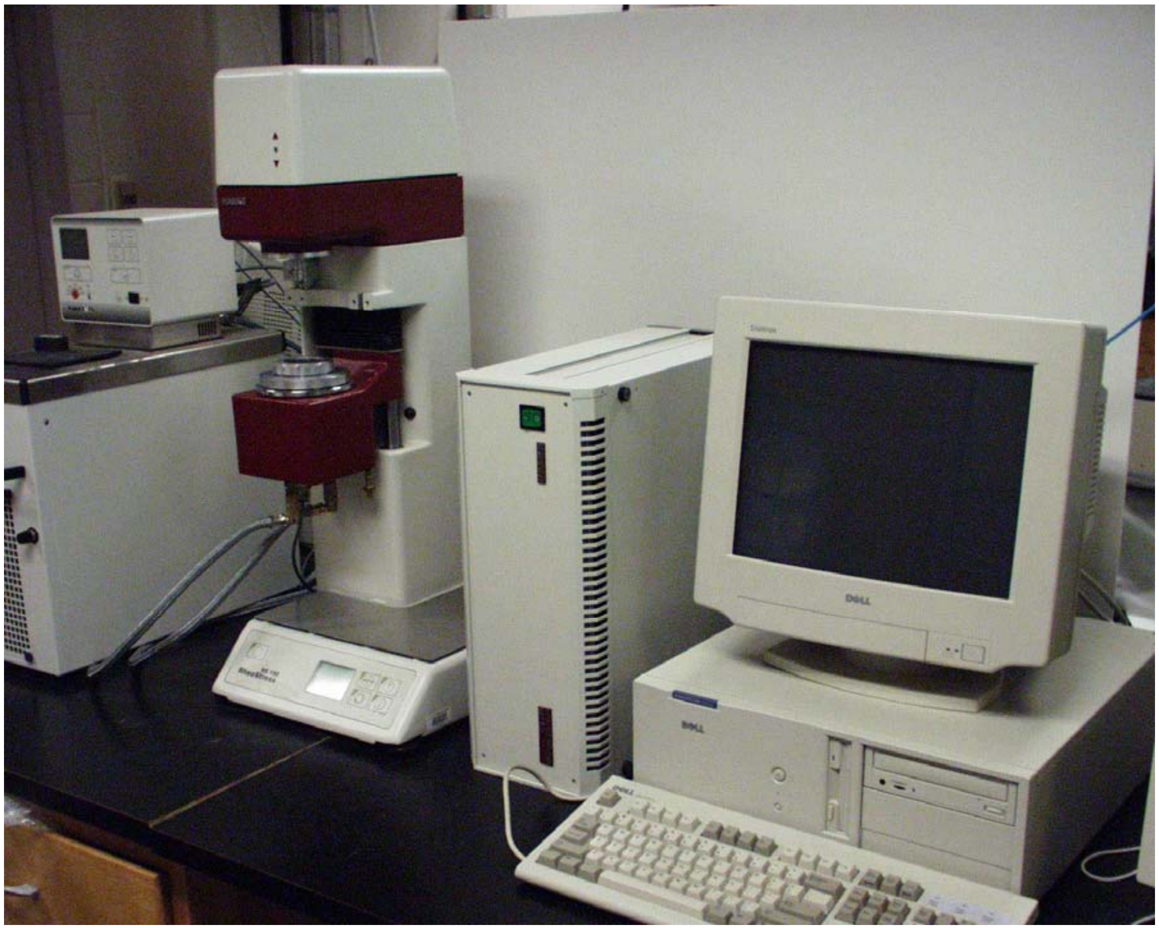


- Low stress required for continuous deformation
  ⇨low viscosity $\left(\eta = \frac{\tau}{\dot{\gamma}}\right)$

- Rheology of the matrix must be controlled to avoid particle segregation (i.e. coarse aggregates)

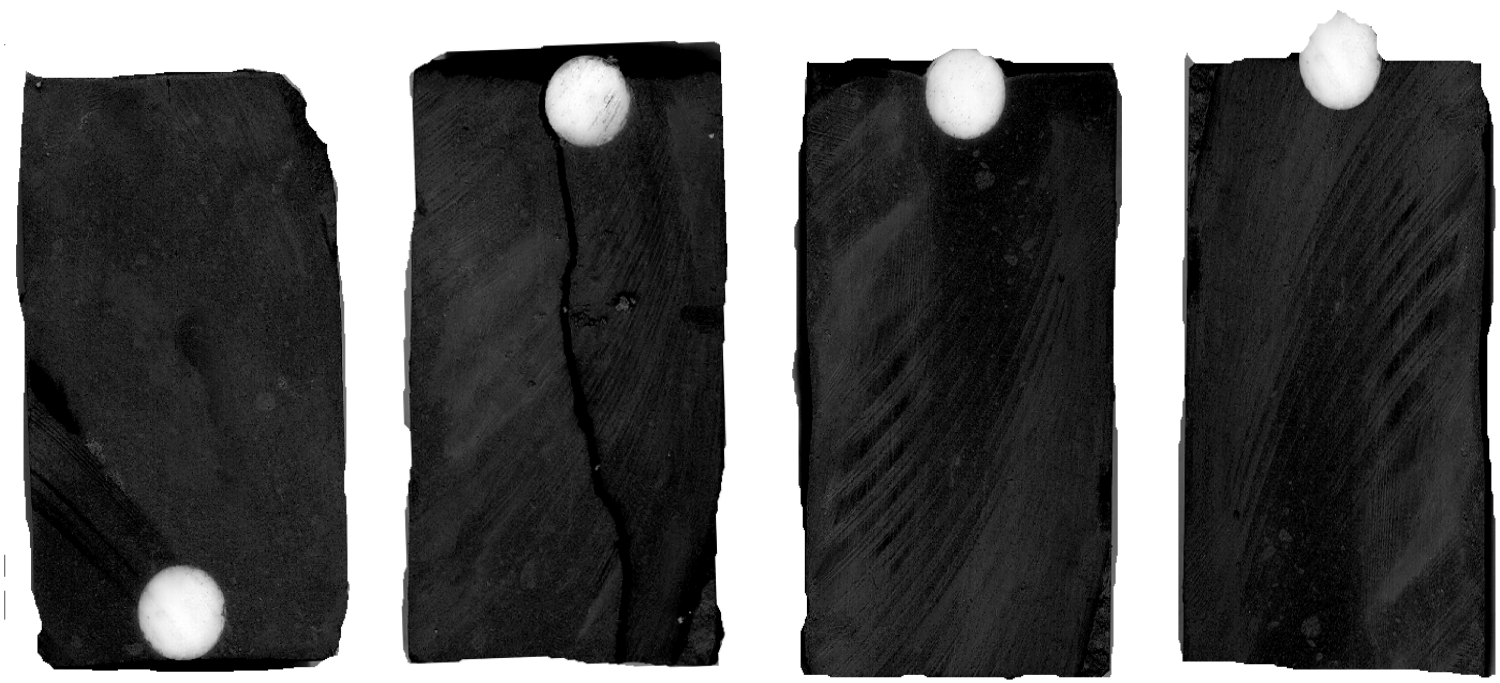


HAAKE-RS150 Rheometer



Influence of Yield Stress

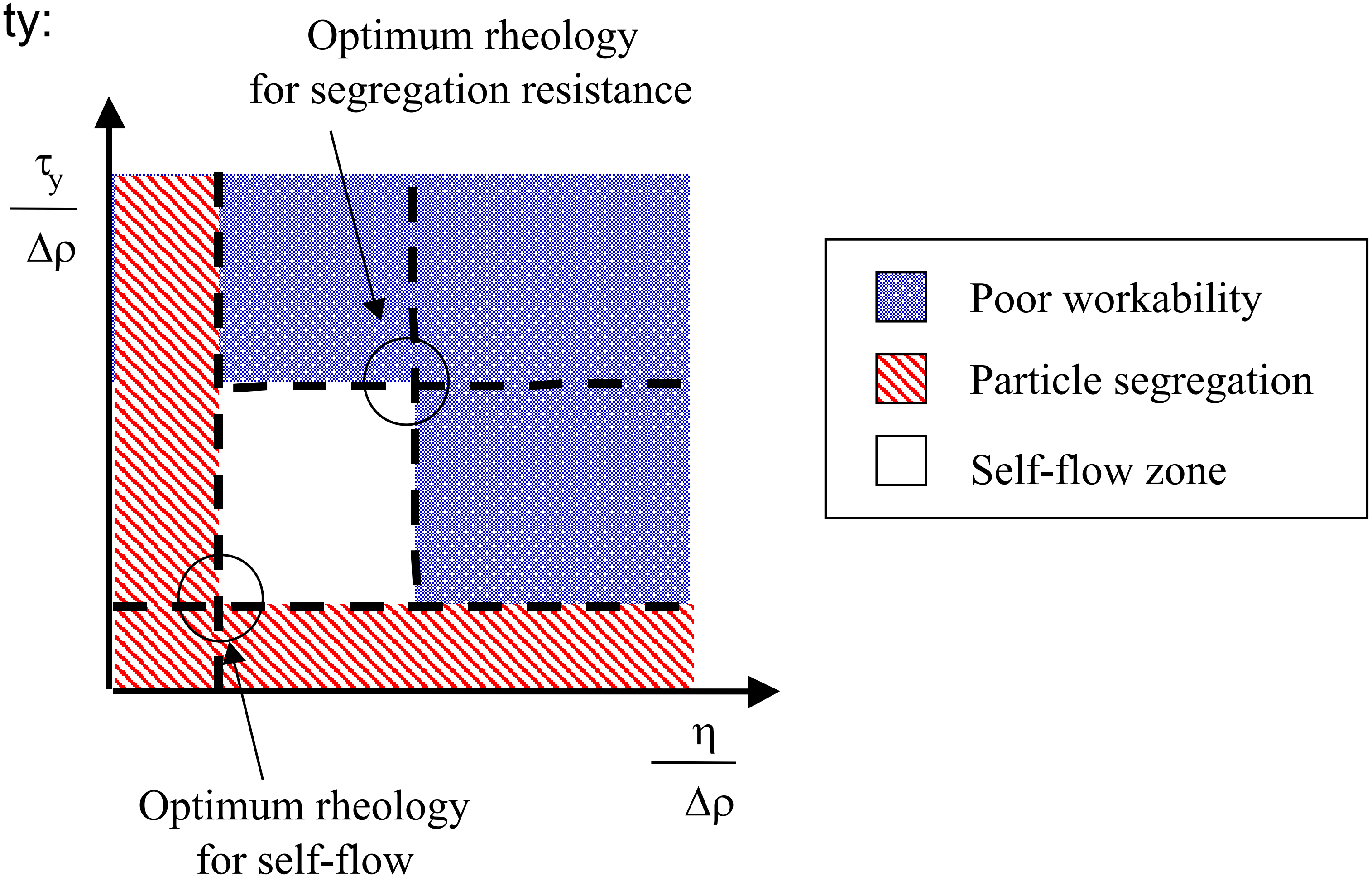
- Yield stress measured using the vane configuration:



2.7 Pa | 25.5 Pa | 31.9 Pa | 141.9 Pa

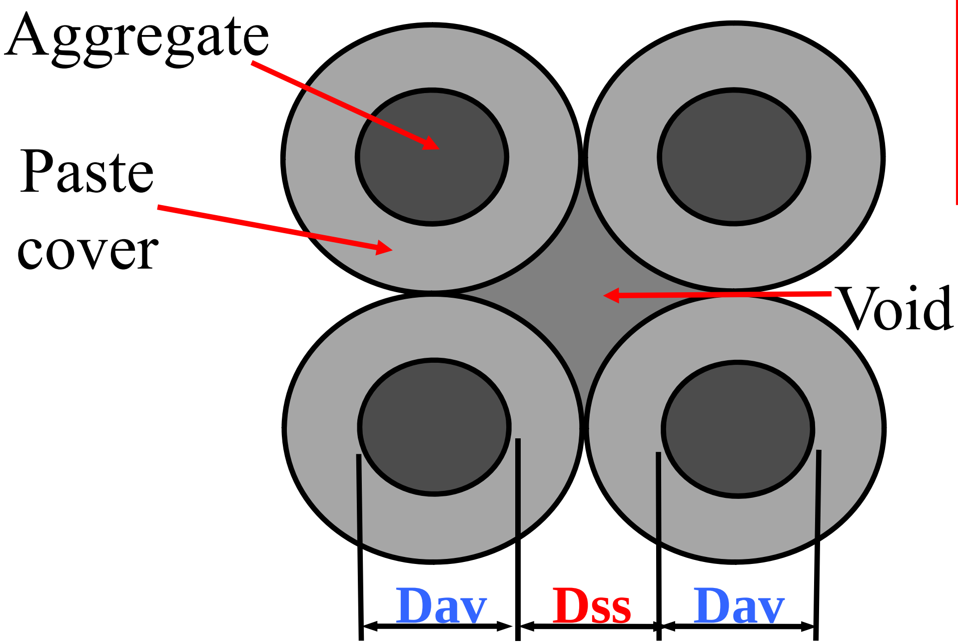
Self-flow Zone Concept

- Matrix yield stress and viscosity must be optimized for self-flowing capability:



Minimum Paste Model

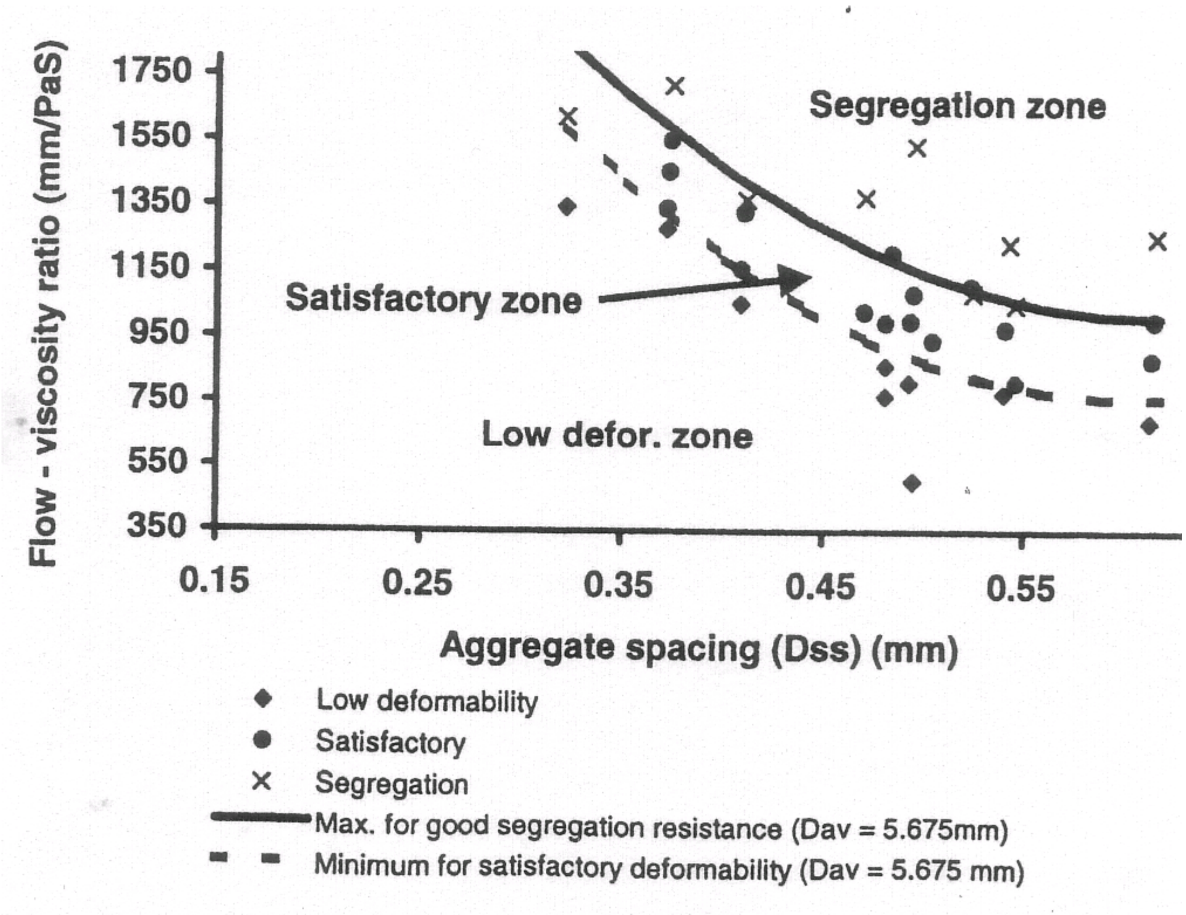
- Minimum Paste Model: accounts for aggregate interaction
  - Min. paste volume needed in to fill voids and coat aggregates
  - Concrete performance predicted through paste matrix
  - Required paste rheology depends on average aggregate spacing (D_{ss}), average aggregate diameter (D_{av}), and density difference between aggregate and paste.



D_{ss} is a function of the void content, average diameter, and aggregate volume (paste volume).

Bui, et.al, ACI Materials Journal 2002

Minimum Paste Model: Self-flow Zone



- *Min. flow and Min. viscosity for good performing SCC*
- *Viscosity and paste flow can not be varied independently*

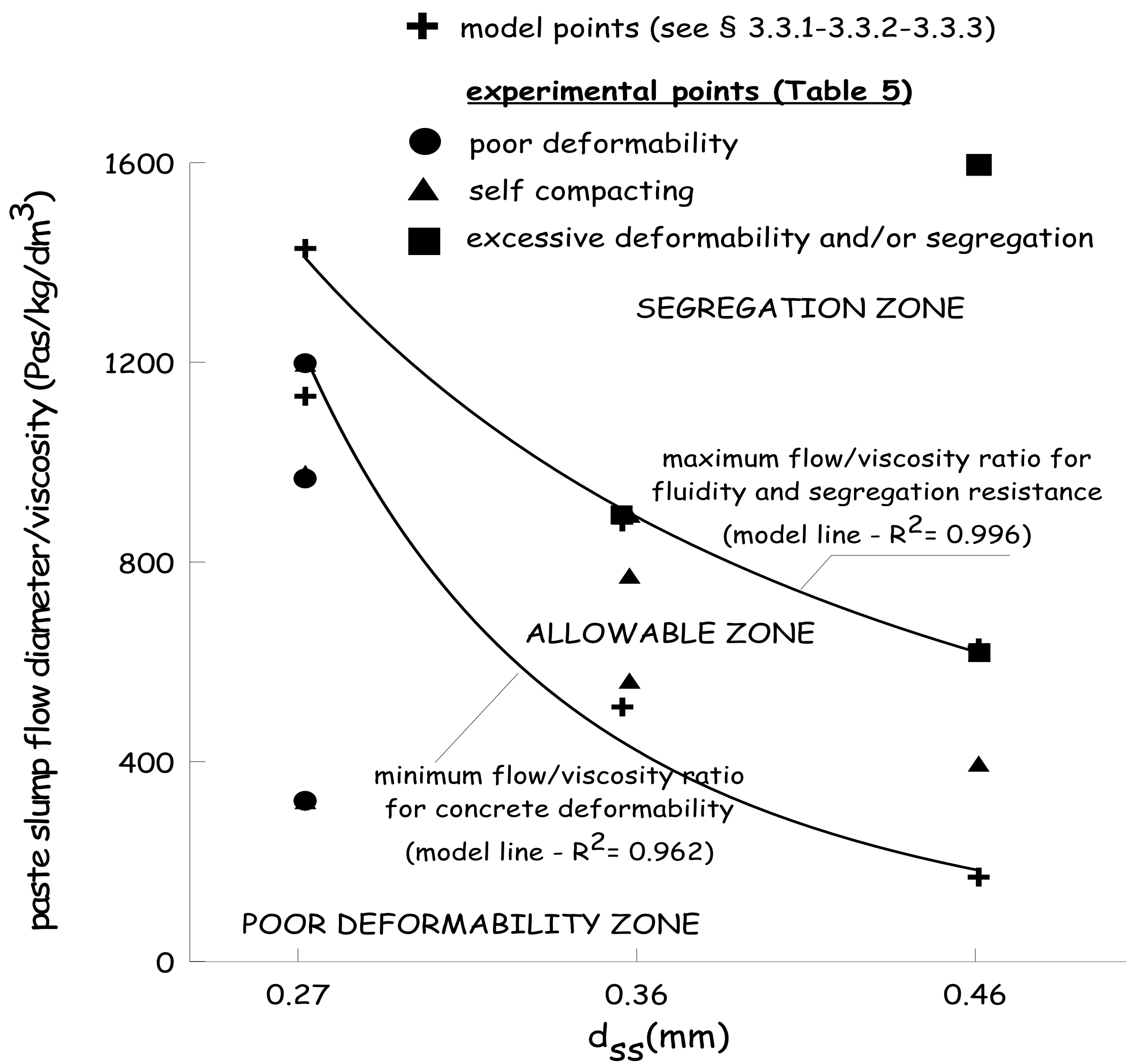
Model is characterized by:

- Min. flow
- Min. apparent viscosity
- Optimum flow/viscosity ratio

Bui, et.al, ACI Materials Journal 2002

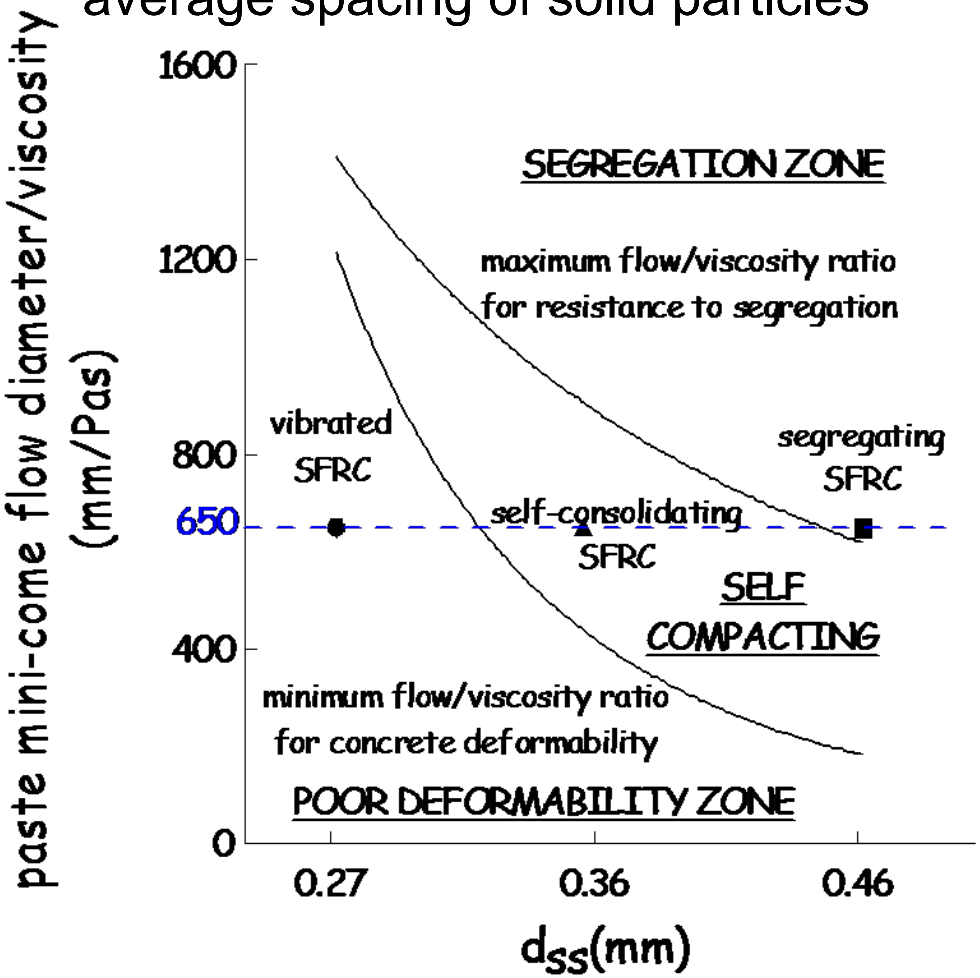
Application of minimum paste model to self-consolidating fiber reinforced concrete (SCFRC)

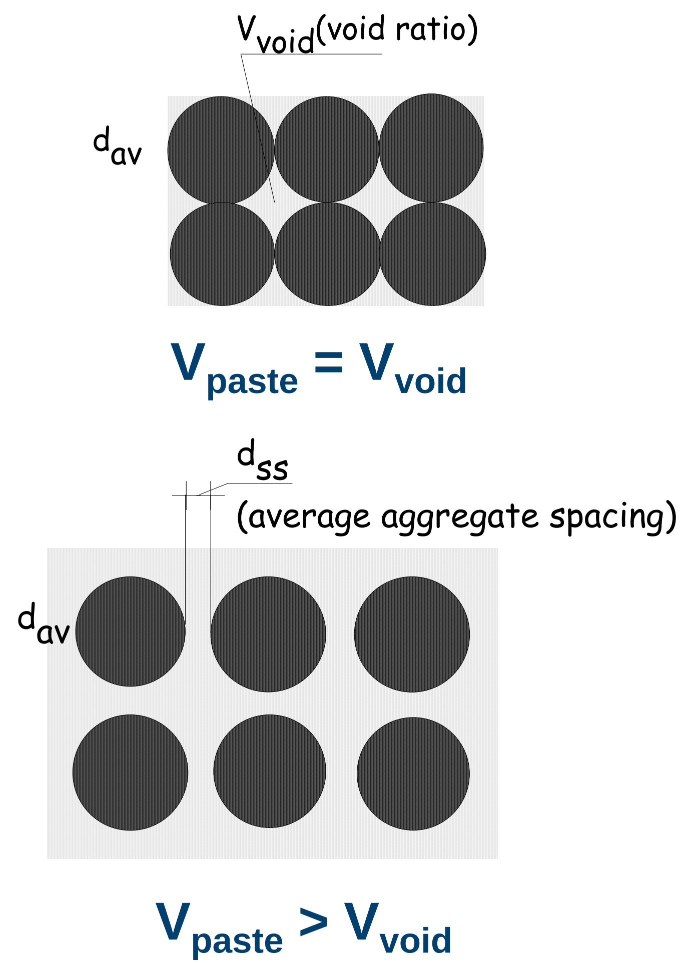
Self-flow Zone for SCFRC



Mix design

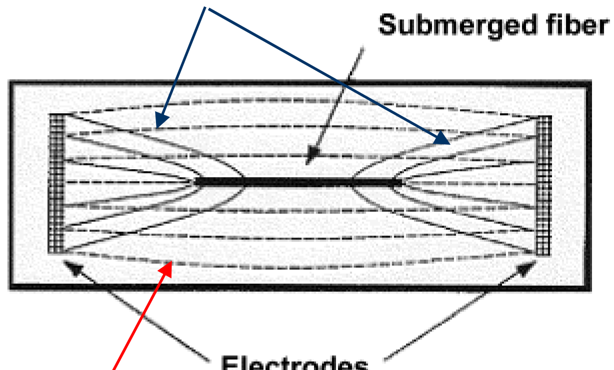
- Optimum flow-viscosity ratio of suspending cement paste vs. the average spacing of solid particles



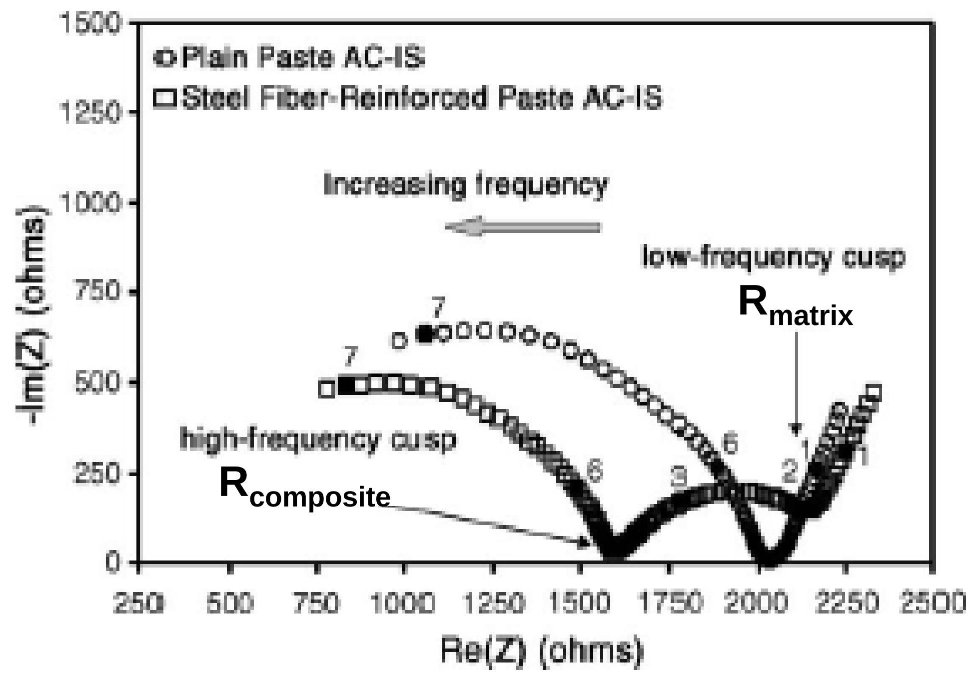


Non-destructive monitoring of fiber dispersion: Alternate Current Impedance Spectroscopy (AC-IS)

Current lines under high frequencies AC
Fibers act conductive



Current lines under low frequencies AC
Fibers act insulating



MATRIX NORMALIZED CONDUCTIVITY

$$\frac{R_m}{R} = \frac{\sigma}{\sigma_m} = 1 + [\sigma]_{fibers} \; V_{fibers}$$

$$[\sigma]_{fibers} = \frac{1}{3}\left[\frac{2(AR)^2}{3\ln(4AR) - 7} + 4\right]$$

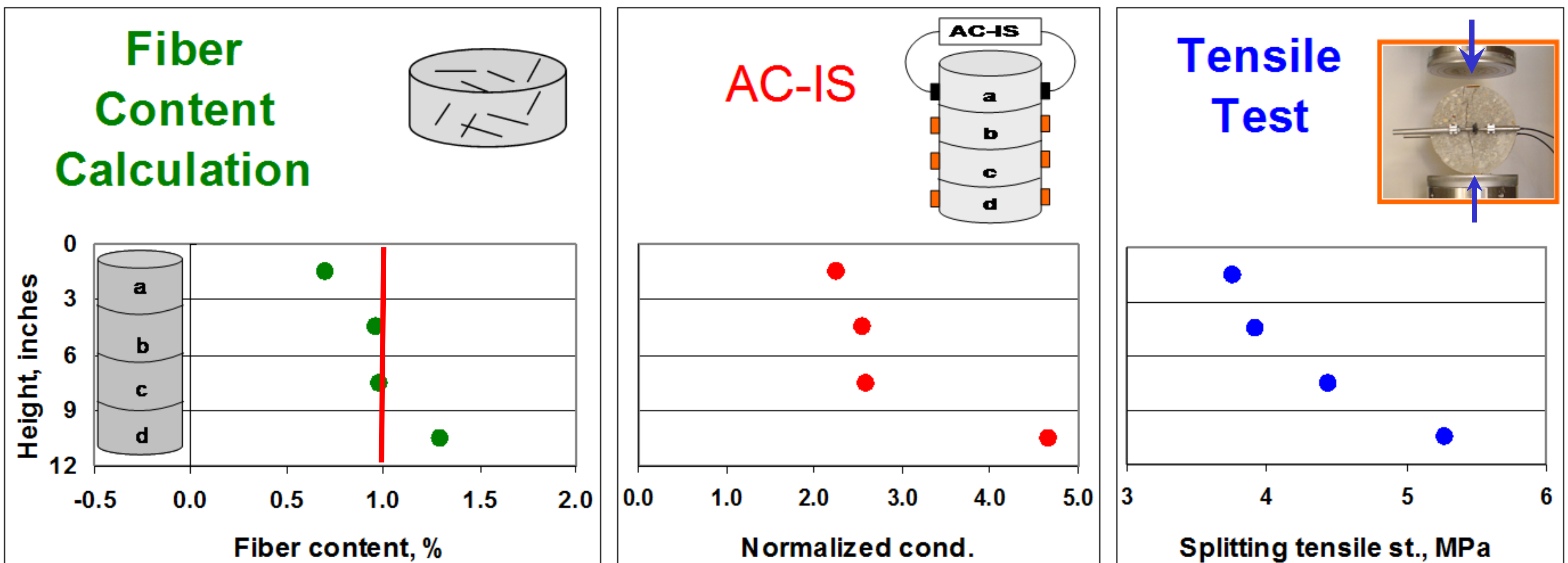
dual arc behavior

Low frequency cusp R_{matrix}: matrix resistance

High frequency cusp $R_{composite}$:
fiber reinforced composite resistance

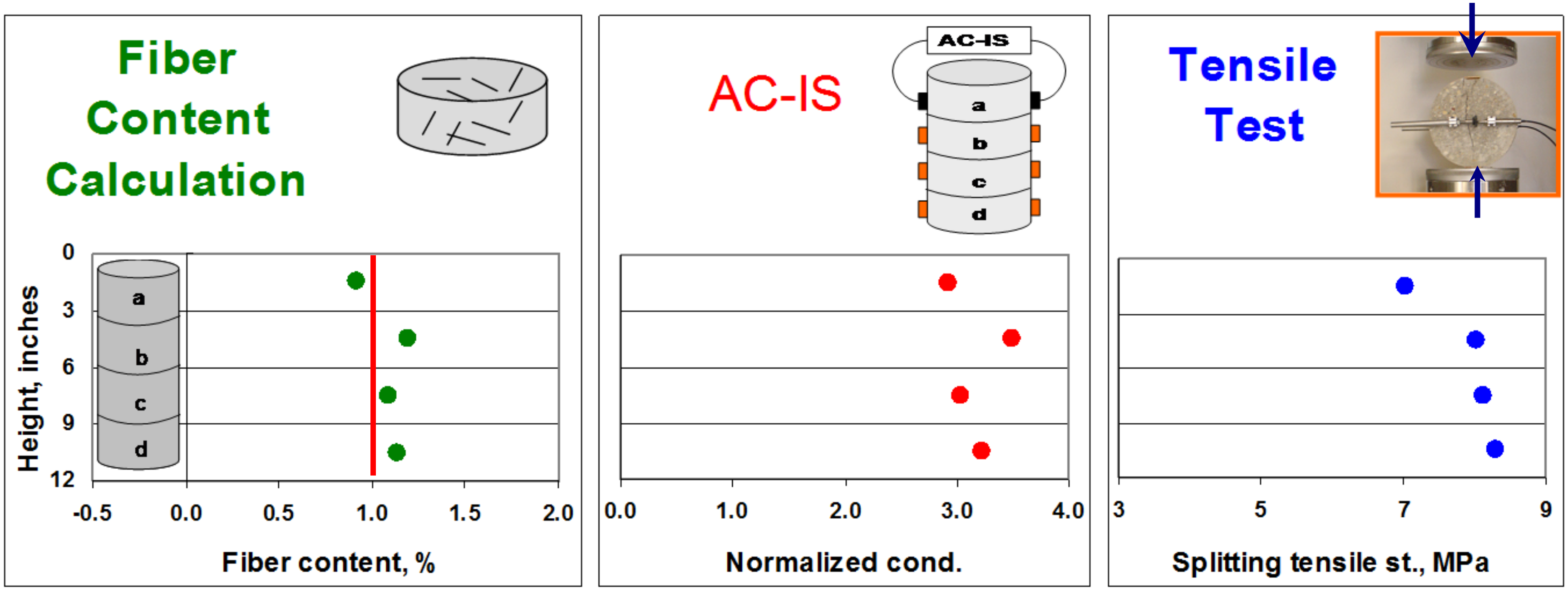
Fiber Segregation

- Conventional concrete:
  - 40 mm fibers, 1 % vol.
  - 2 min. vibration

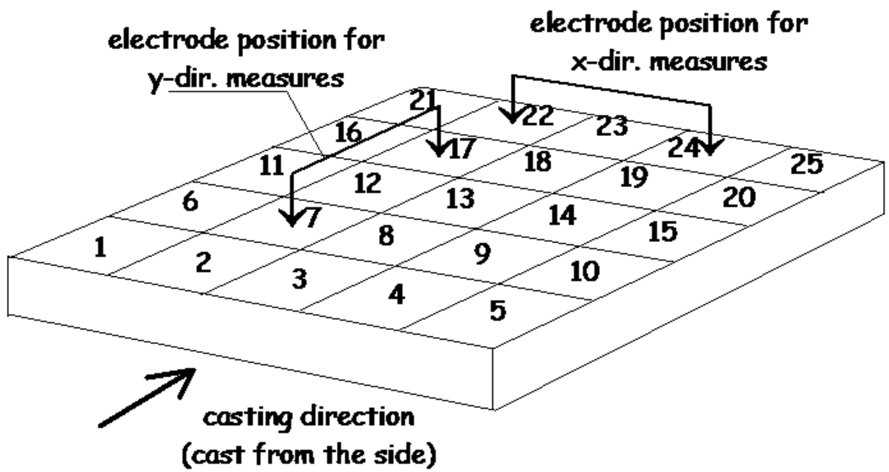


Fiber Segregation

- Self Consolidating Concrete
  - 40 mm steel fibers,
  - 1 % vol.



Non-destructive monitoring of fiber dispersion: Alternate Current Impedance Spectroscopy (AC-IS)

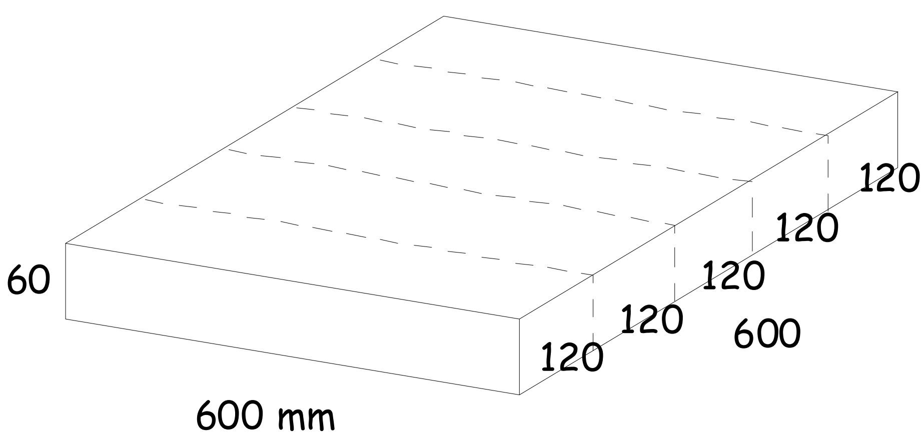


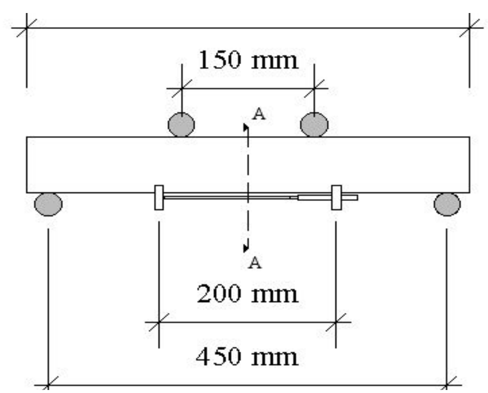
Vibrated SFRC

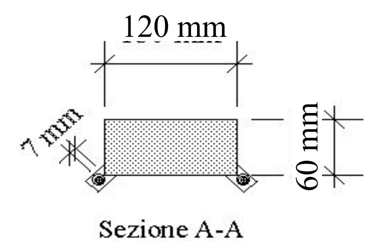
Self Consolidating SFRC

Segregating SFRC

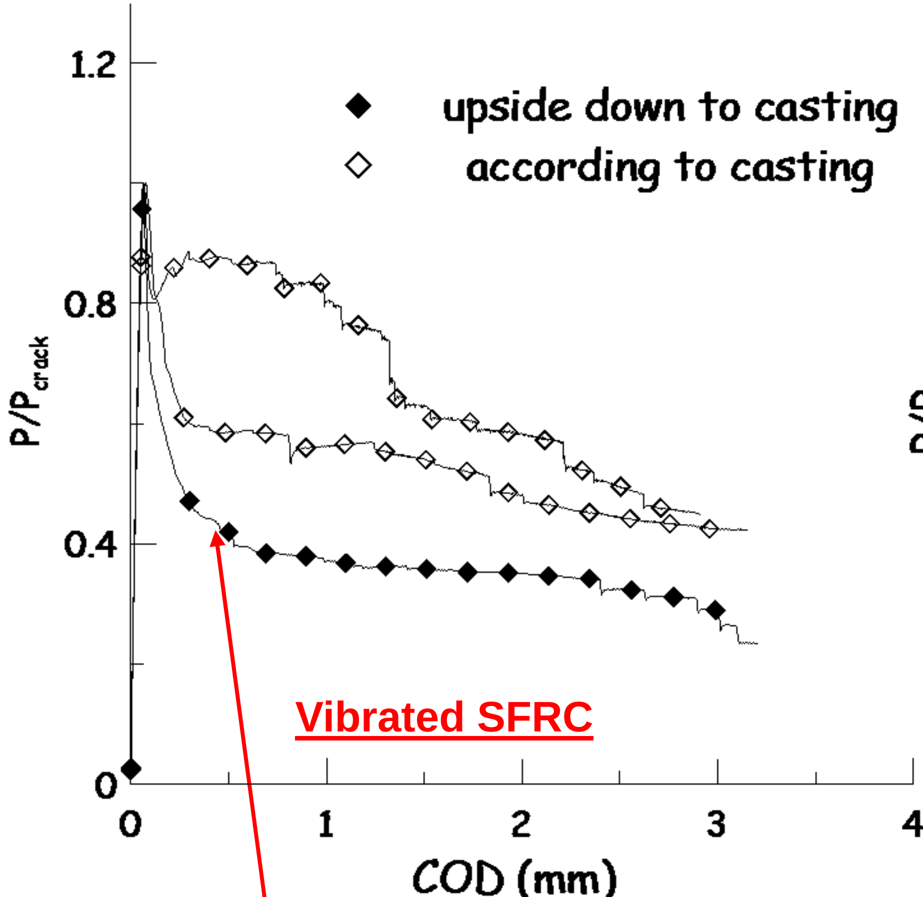
After AC-IS measurements cut beams from the plates and test in 4 point bending

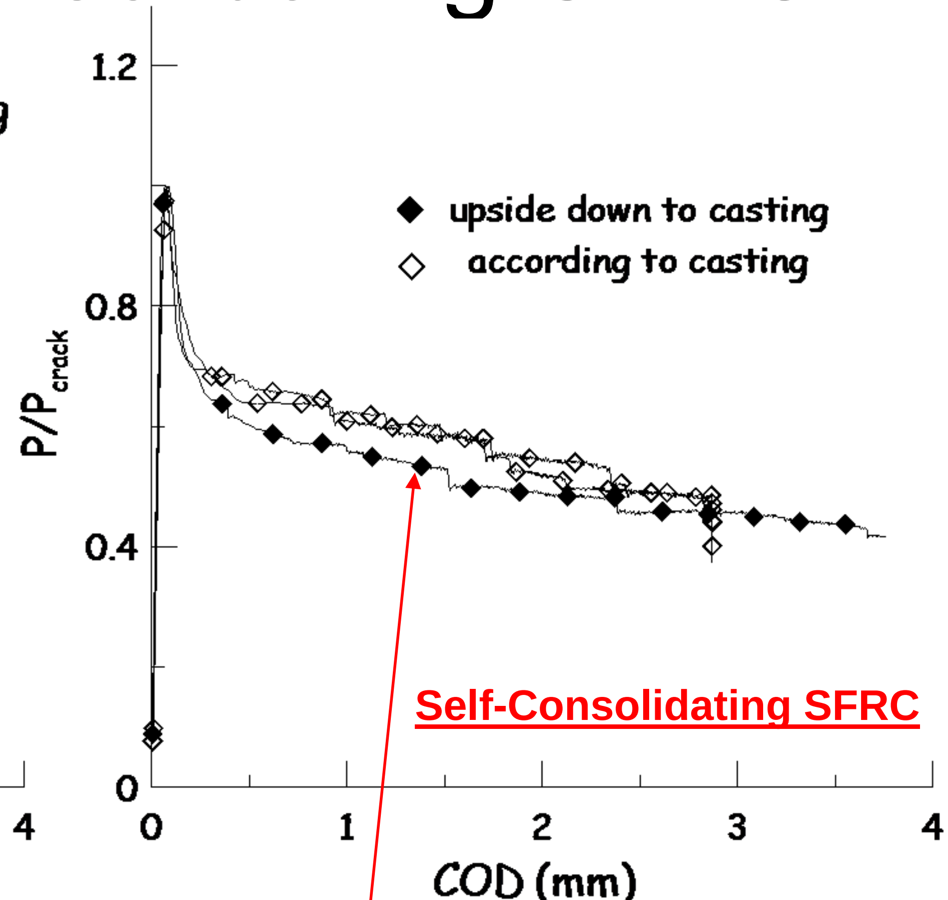






Four-point bending: vibrated vs. self consolidating SFRC





Strong segregation

High scattering for companion specimens (cut from the same slab)

No segregation

Low scattering for companion specimens (cut from the same slab)

Casting with SCC

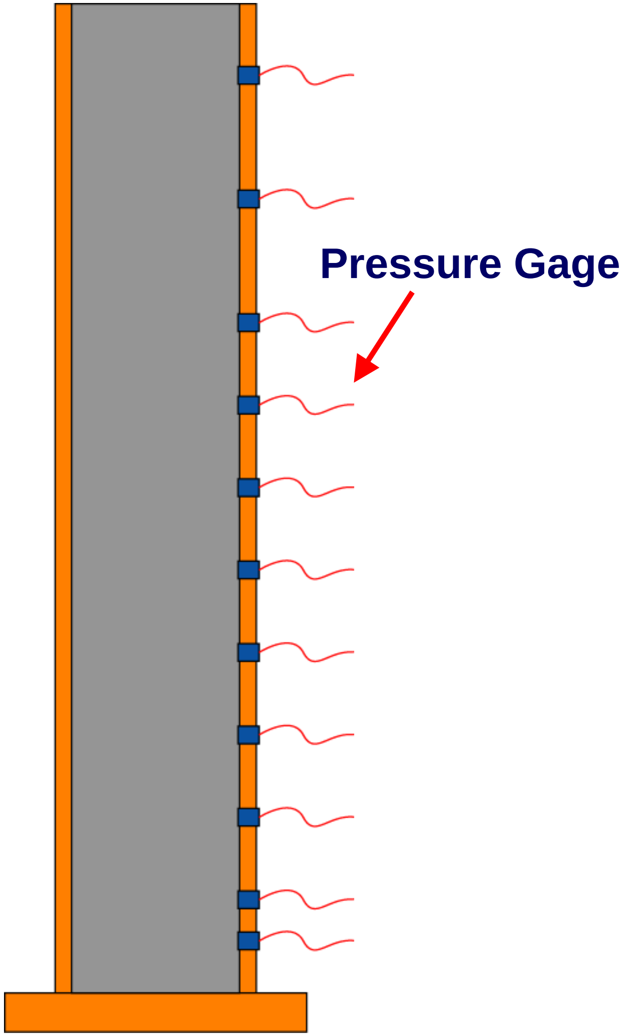
One advantage of SCC is increase in construction due to higher casting (rates can exceed 100 m/h).

However, ↑ Casting Rate ↑ Formwork pressure

- Therefore, SCC formworks are typically designed for hydraulic pressures.

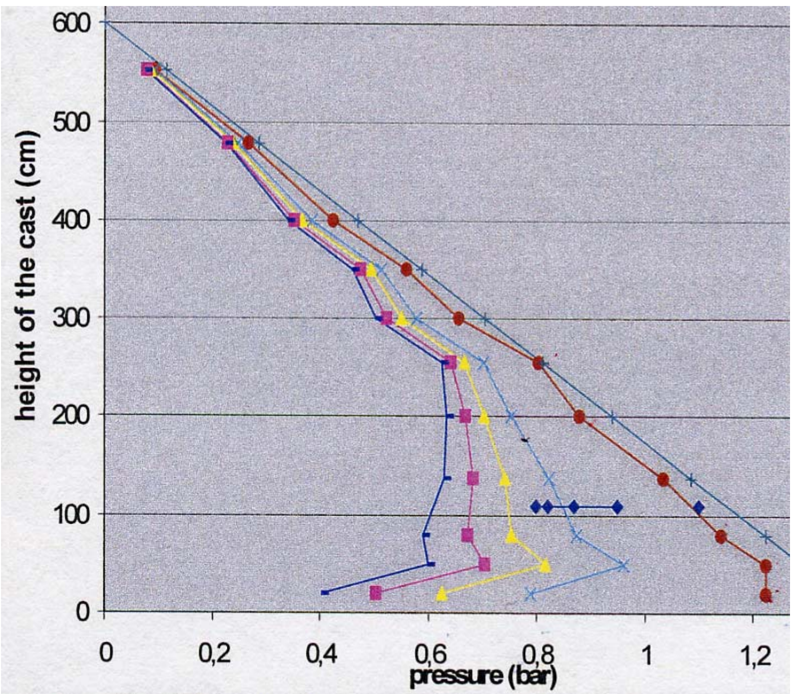
SCC Formwork Mock-up Test

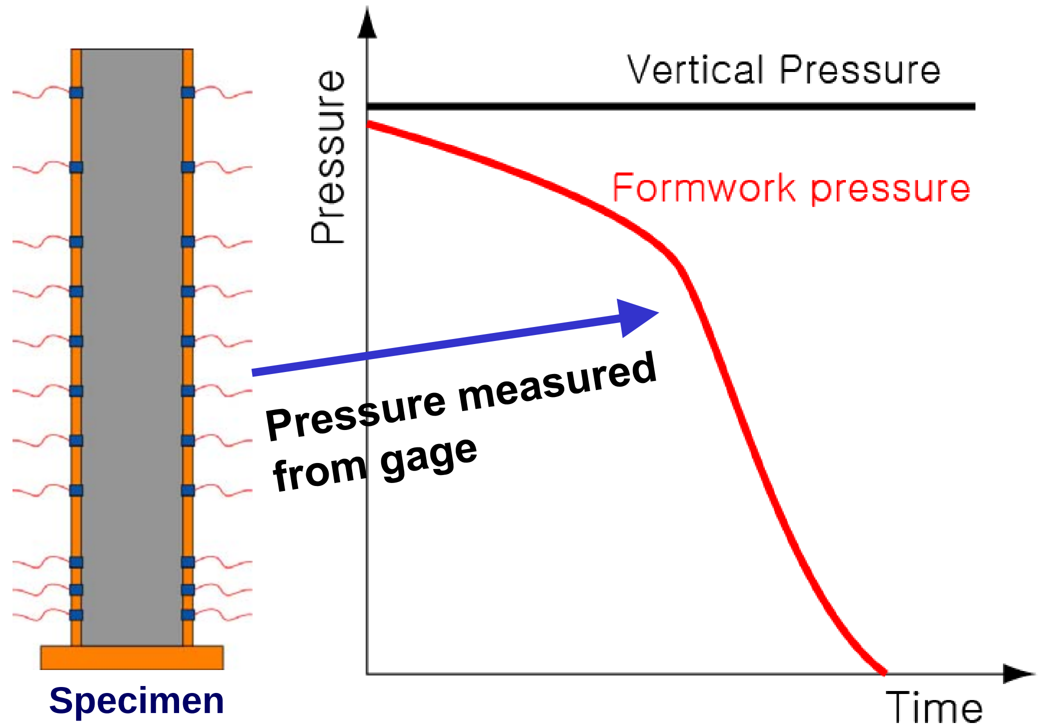
Mock Up Test (2007, Dante Galeota, and et al.)



Specimen

Pressure Profile





Mock Up Test (2007, Dante Galeota, and et al.)

Research Program

Goal

Reduction of the formwork pressure

- **Reduce the initial formwork pressure**
- **Decrease the cancellation time of formwork pressure**

Research Branch

Understanding of Fundamental Mechanisms

- **Develop protocol to evaluate structural rebuilding**
- **Understand effect of material constituents on rheology and flocculation**
- **Simulation of flow behavior**

Application in Practice

- **Development of test method and laboratory test apparatus**
- **Development of prediction model for formwork pressure**

Laboratory Setup for Formwork Pressure Measurement

- Simulation range: Real scale column heights up to 20 m, and casting rates ranging from 0 m/hr to 25m/hr

Lab formwork

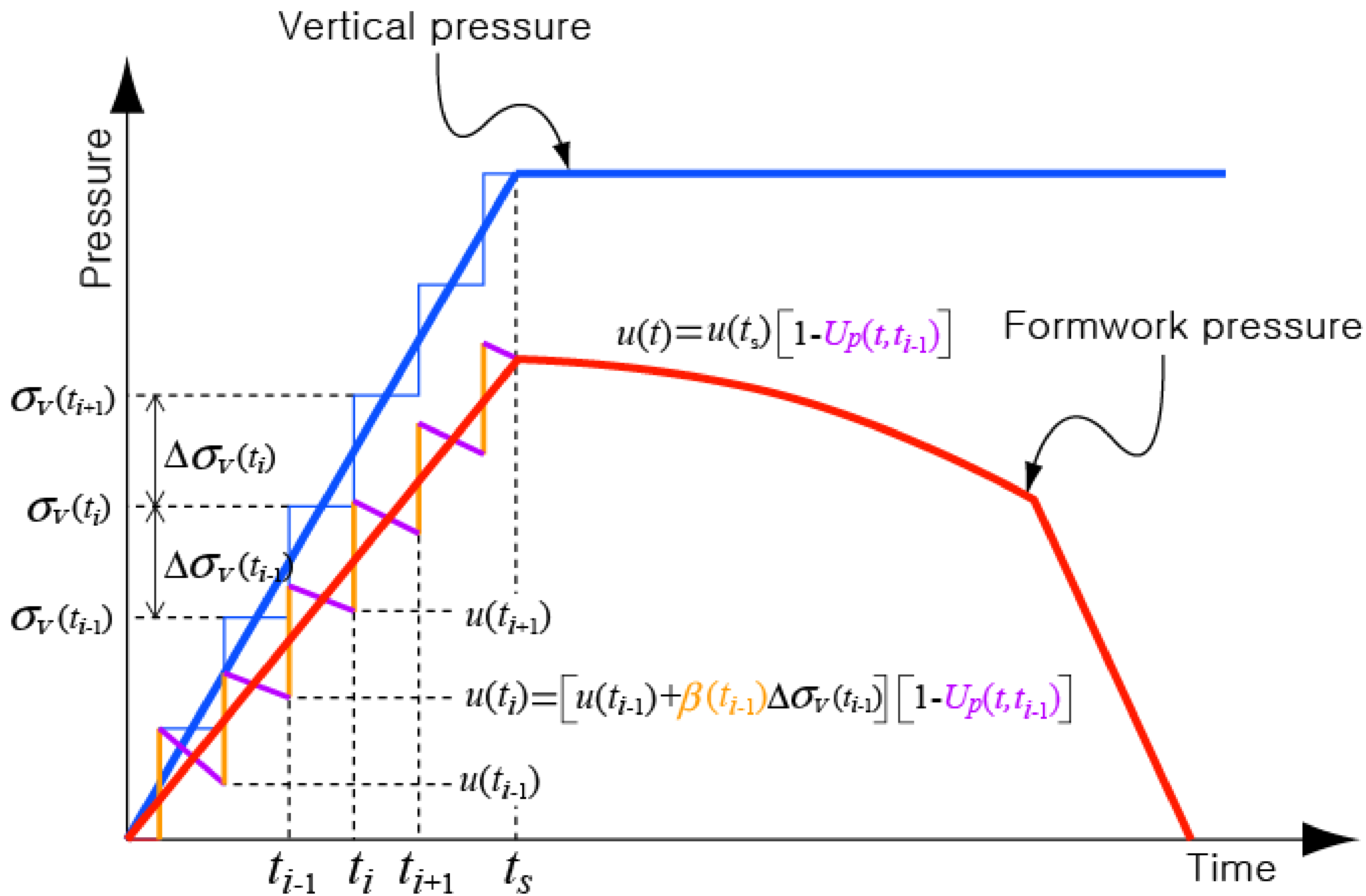
(V~20 Liter, H= 45cm, D=23 cm)

Pressure Sensors

(capacity: 50psi = 344kPa)

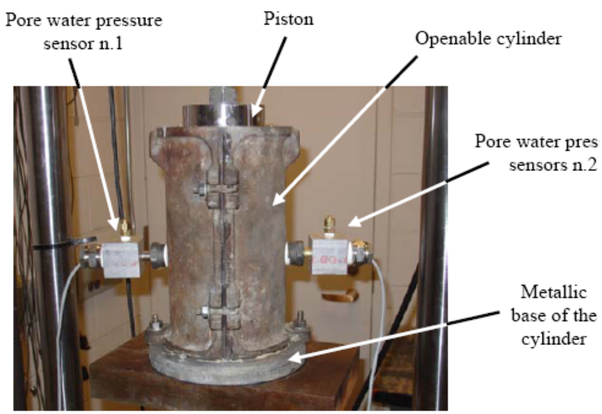
Loading Cell

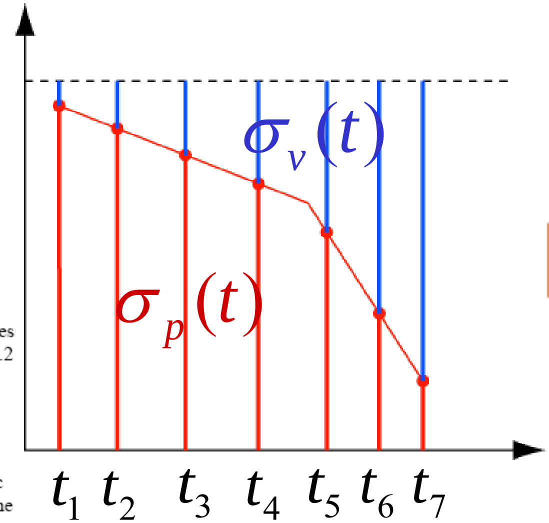
Prediction of Formwork Pressure

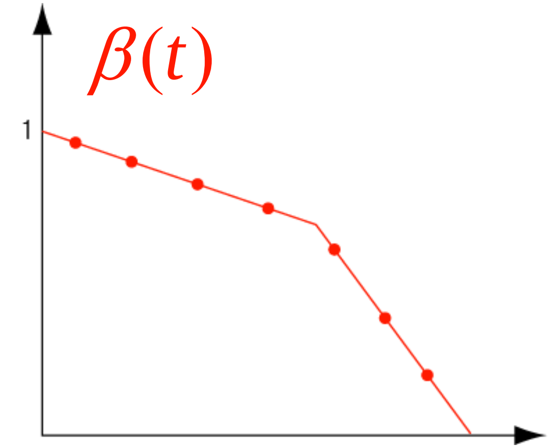


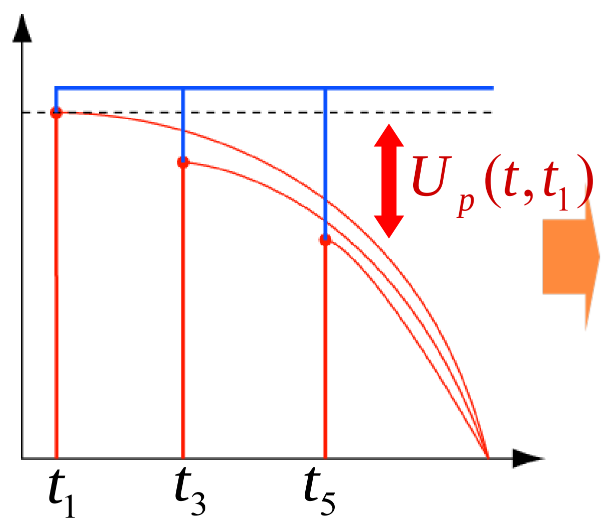
Tests to Find $U_p(t,t')$ and $\beta(t)$

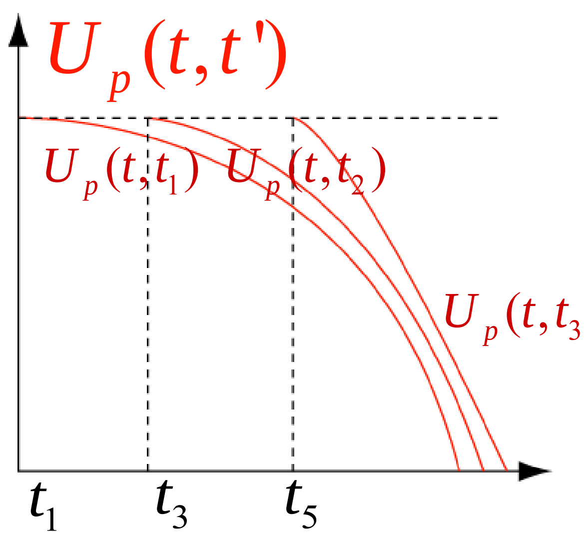
$\beta(t)$ $U_p(t,t')$



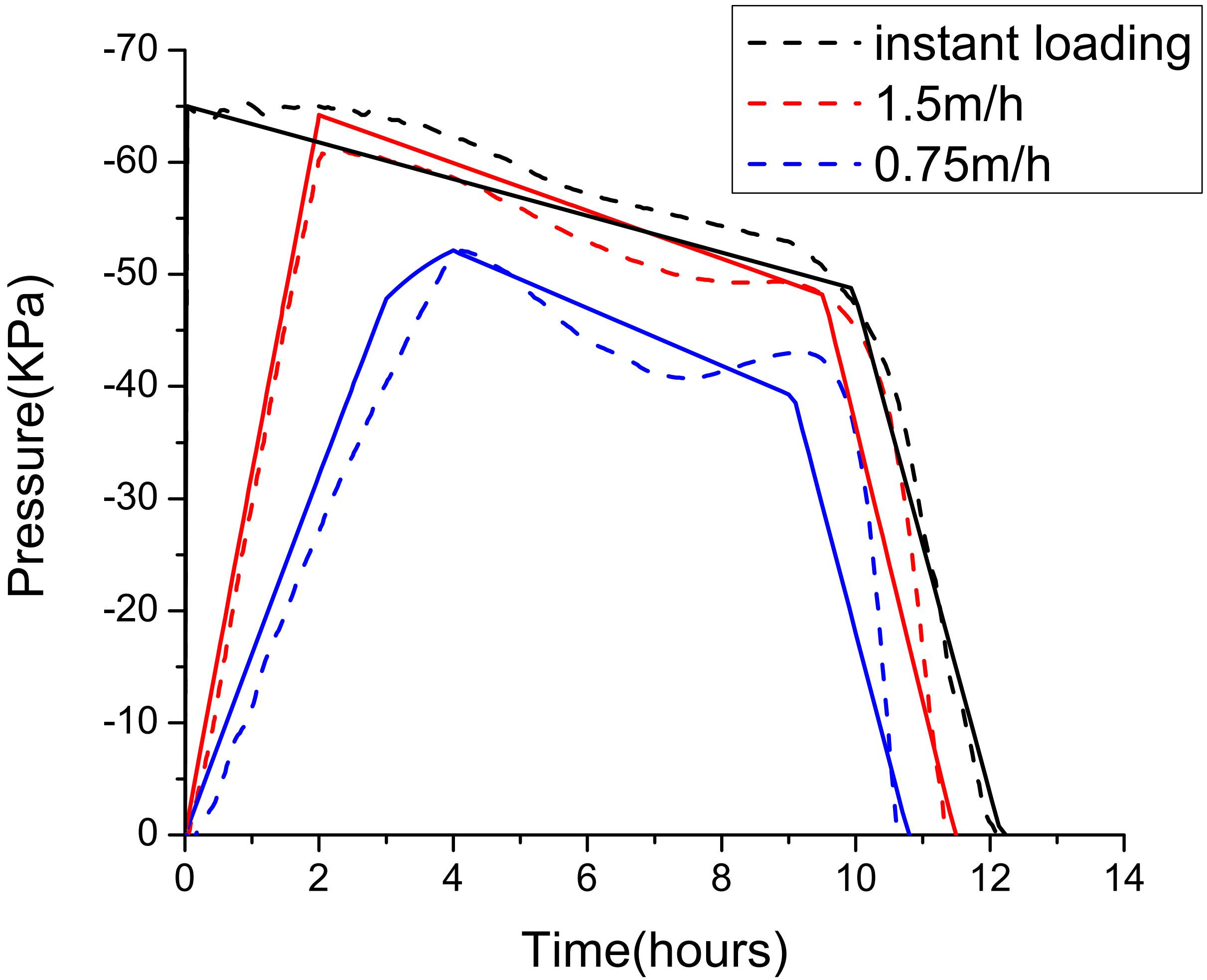




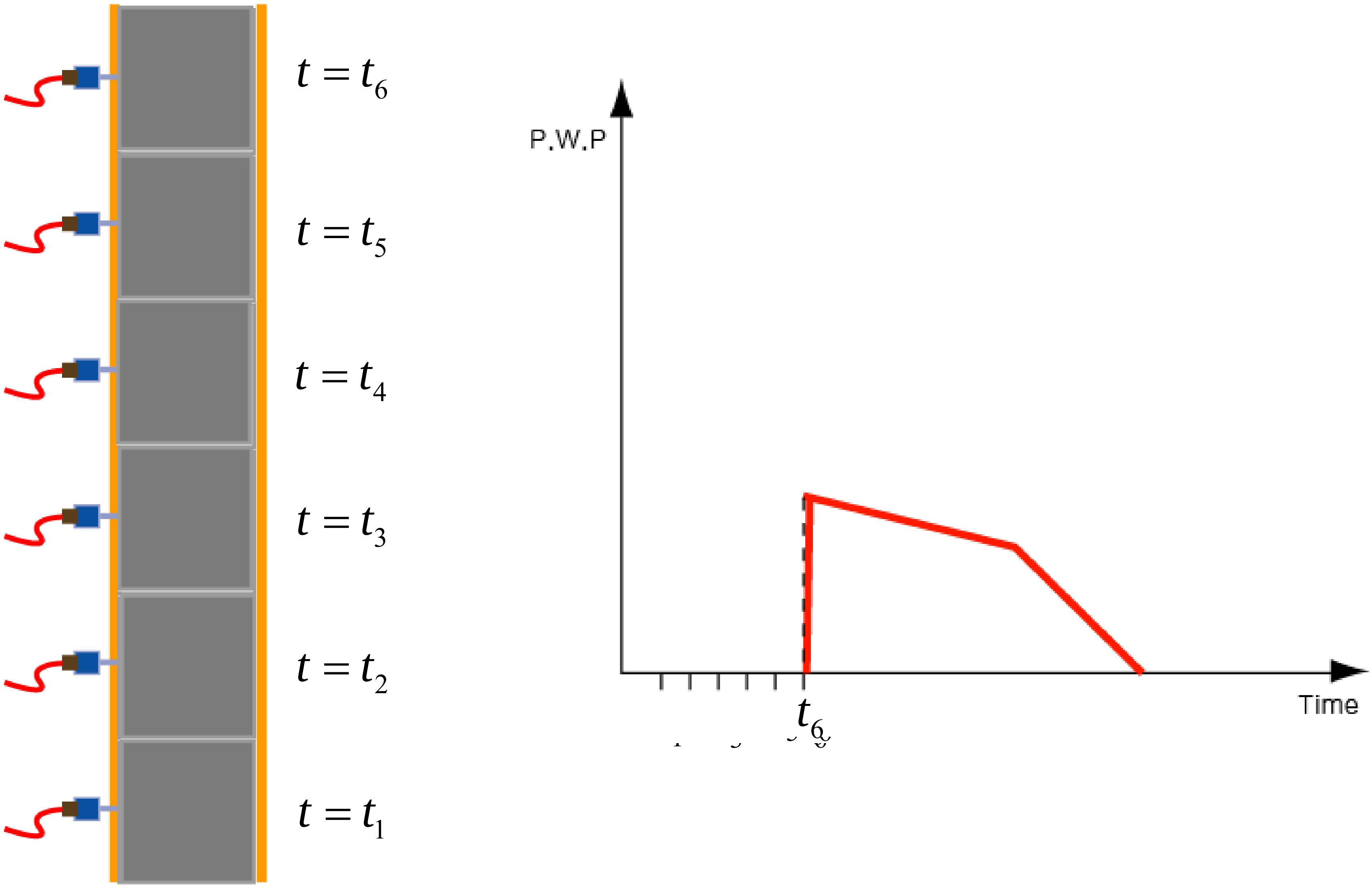




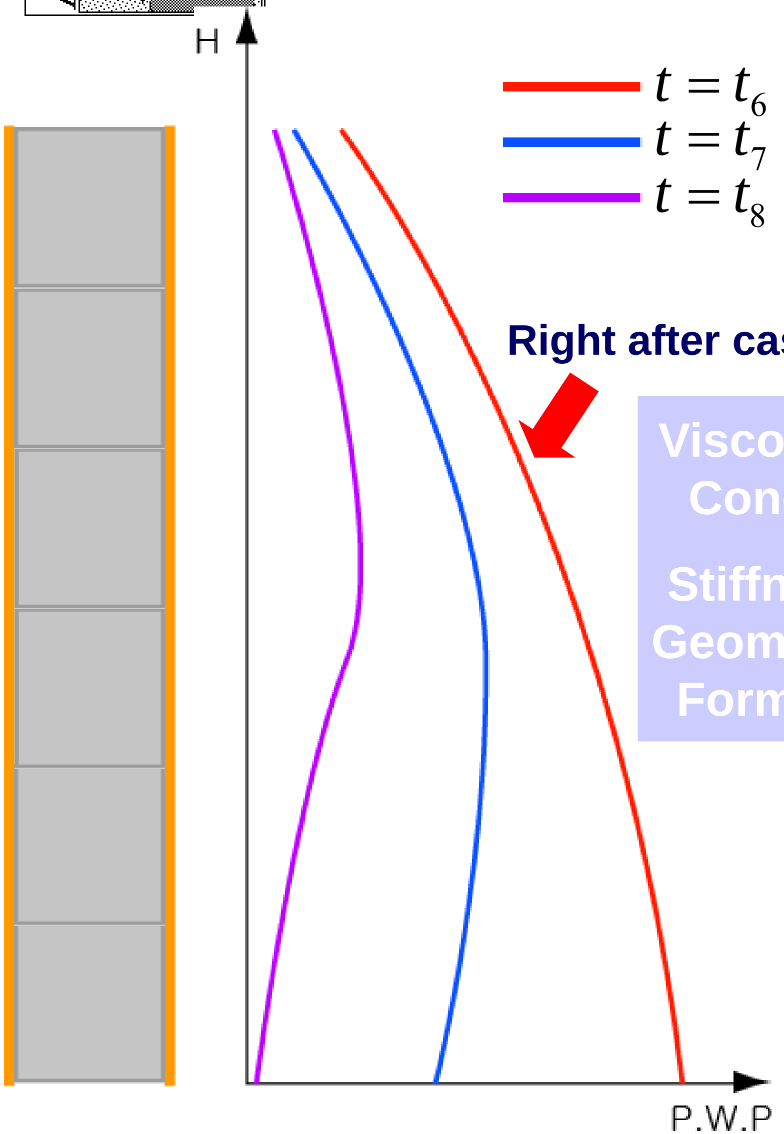
Calculation of Formwork Pressure Based on New Assumption



Calculation of Formwork Pressure



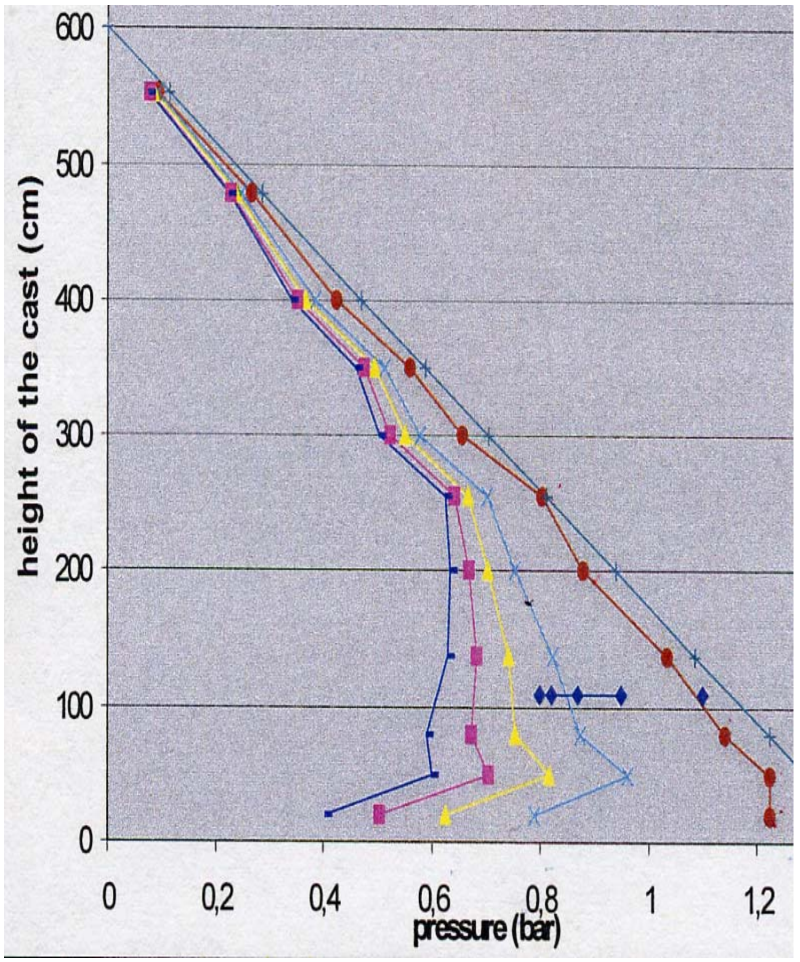
Calculation of Formwork Pressure



Viscosity of Concrete

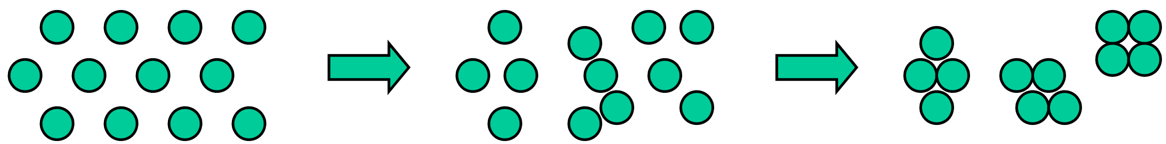
Stiffness & Geometry of Formwork

Mock Up Test
(2007, Dante Galeota, and et al.)

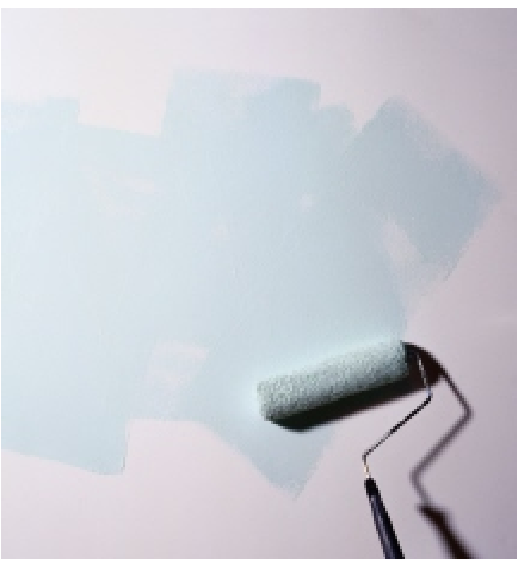


Flocculation: Aggregation of Colloidal Particles

Flocculation is the formation of flocs within a liquid/solid suspension



Where is flocculation important? Why is flocculation important?



Paints

Extruded Ceramics

Emulsions

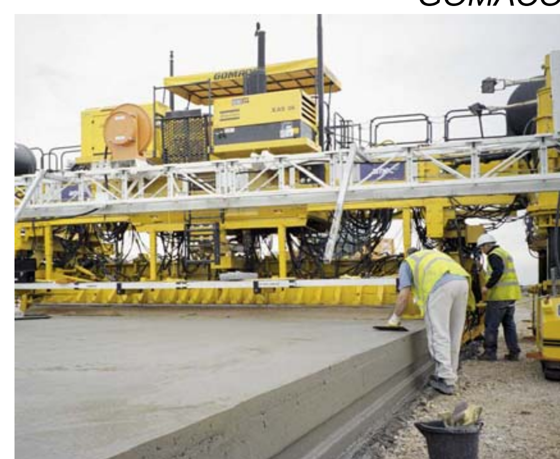
Flocculation is involved in a wide variety of applications!

Applications to Cement

- Self consolidating concrete (SCC)
  - Requires stable suspension in order to provide workability
- Extrusion
  - Requires workability but also fast rebuilding upon processing
- Improving the slipform paving process
  - Combination of both

Zhen 2006

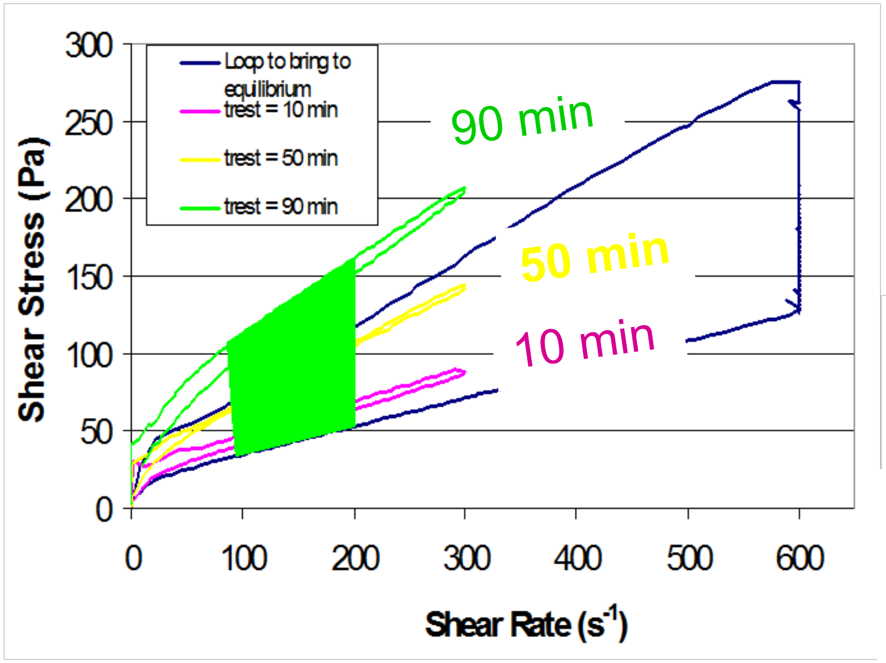
GOMACO

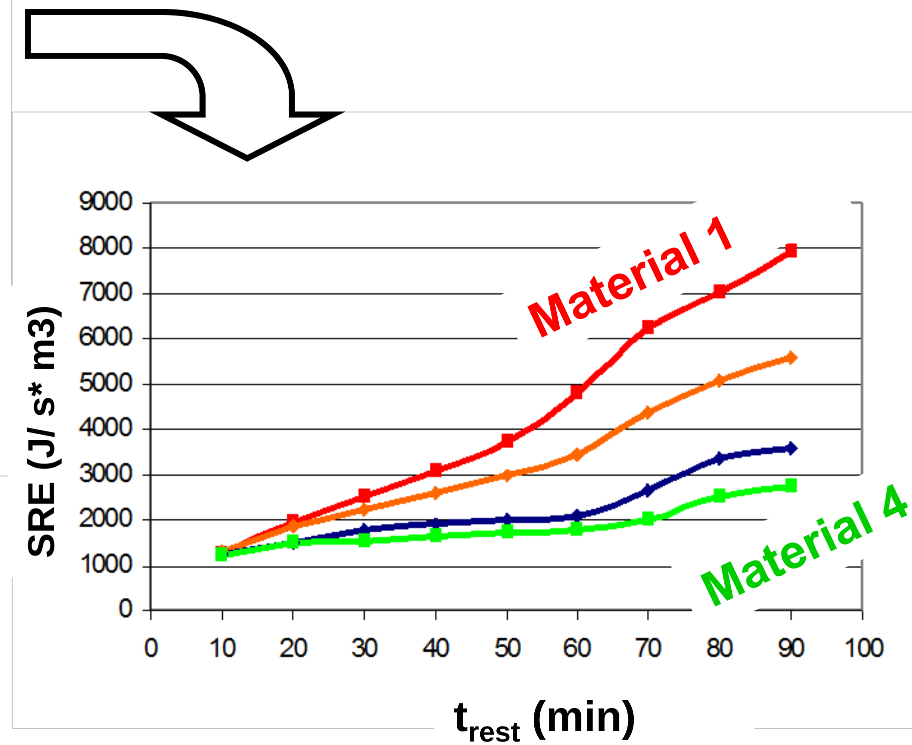


Structural Build-up of Cementitious Materials

- Irreversible
  - Hydration mechanisms
- Reversible
  - Thixotropy: time dependent change in viscosity
    - Particle flocculation (zeta potential, changes in chemistry, etc)
- *How to measure structural build-up during dormant period?*
- Hydration
- Rheology
- Imaging
- Particle size evolution
- Changes in chemistry

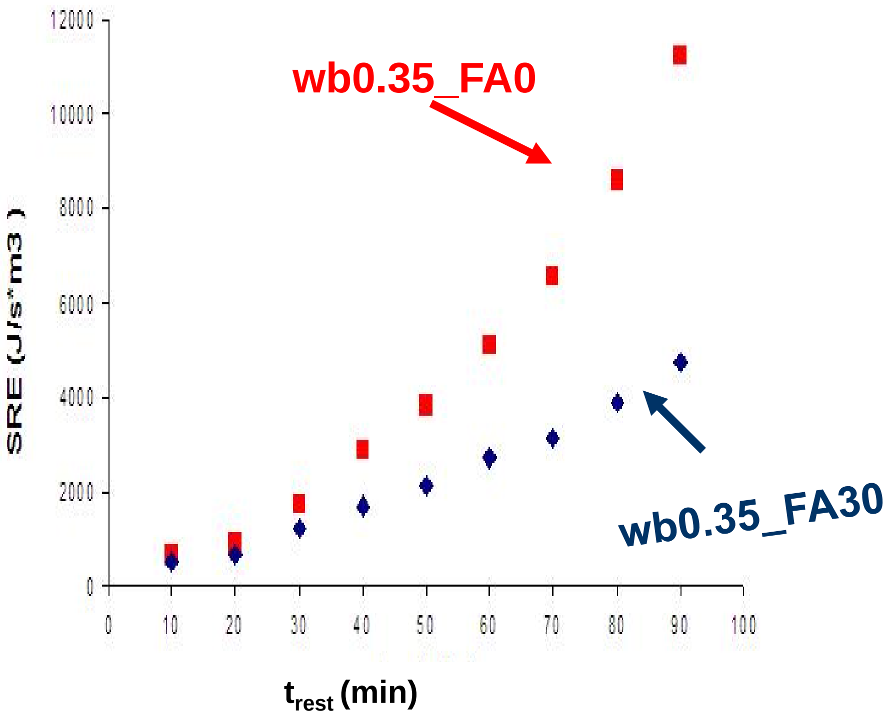
Rheological Protocol to Measure Structural Rebuilding



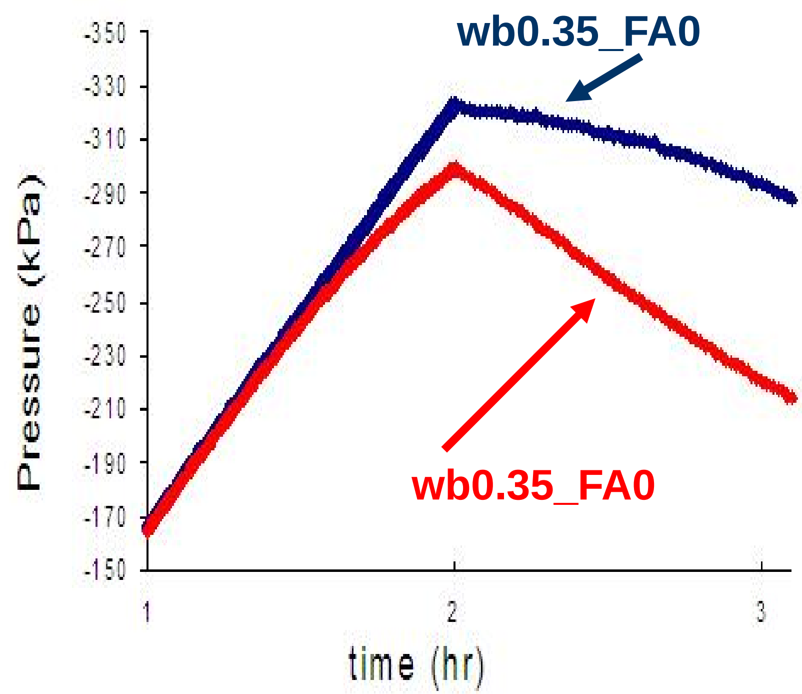


Relating Rebuilding and Formwork Pressure

- Structural Rebuilding of cement paste:
- Formwork pressure simulation of cement paste (H = 14m, R = 7m/hr)



Flow diameter = 33 cm



Flow diameter = 33 cm

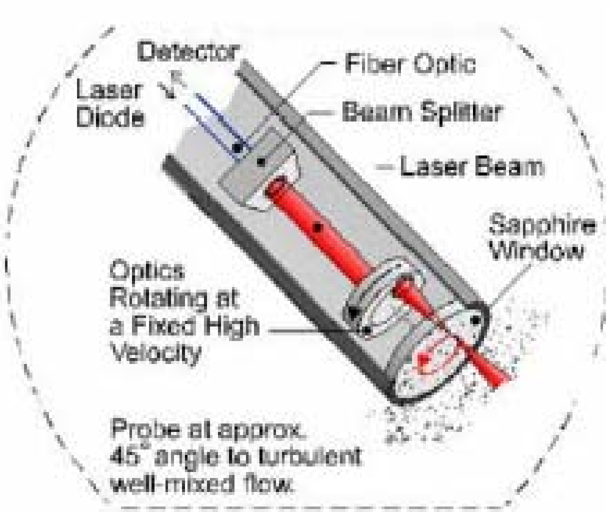
FBRM: A Way to Measure Floc Size

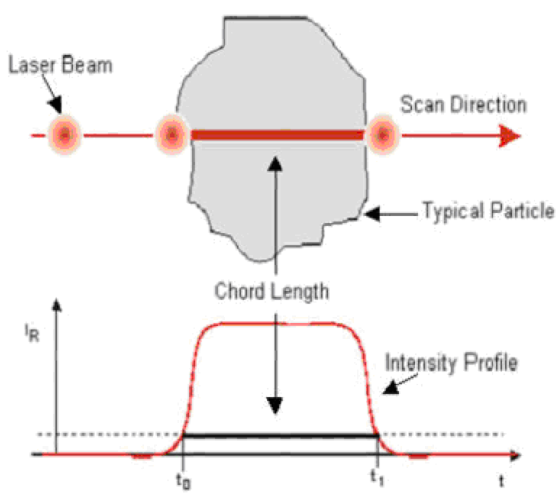
Focus Beam Reflectance Measurement (FBRM):

Gives information about Floc size →indirect indication of flocculation

- *in situ*/in-line information about the evolution and size of particle

- scans highly focused laser beam across suspension and measure time duration of back scattered light





(Mettler-Toledo, 2005)

- Time taken for beam to scan is measure of particle size
- Focus beam cross particle on a straight line between any 2 points.
- Hundreds of thousands of chords are measured per second
- Chord length range: 0.5 – 1000 µm

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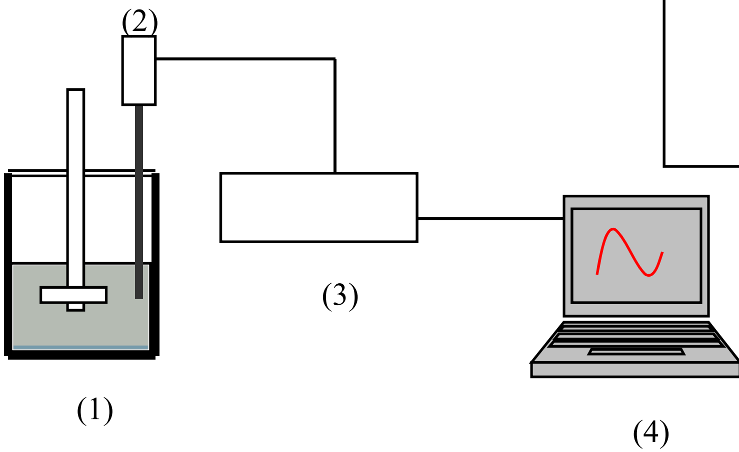
FBRM Set-up

(1) Mixing vessel
(2) FBRM probe
(3) Processing unit
(4) PC for data logging and analysis



Agitator

FBRM
PROBE

400 ml Sample

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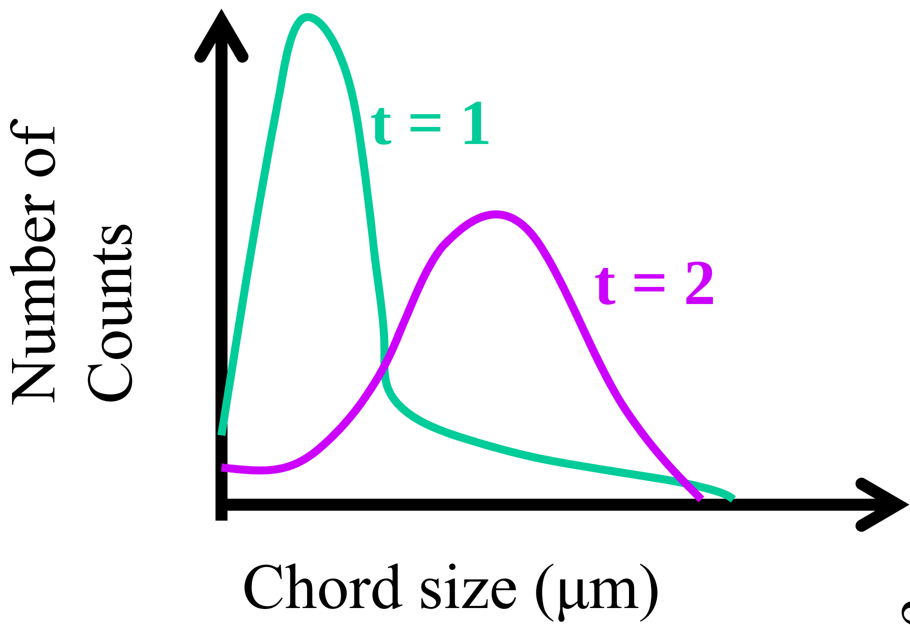
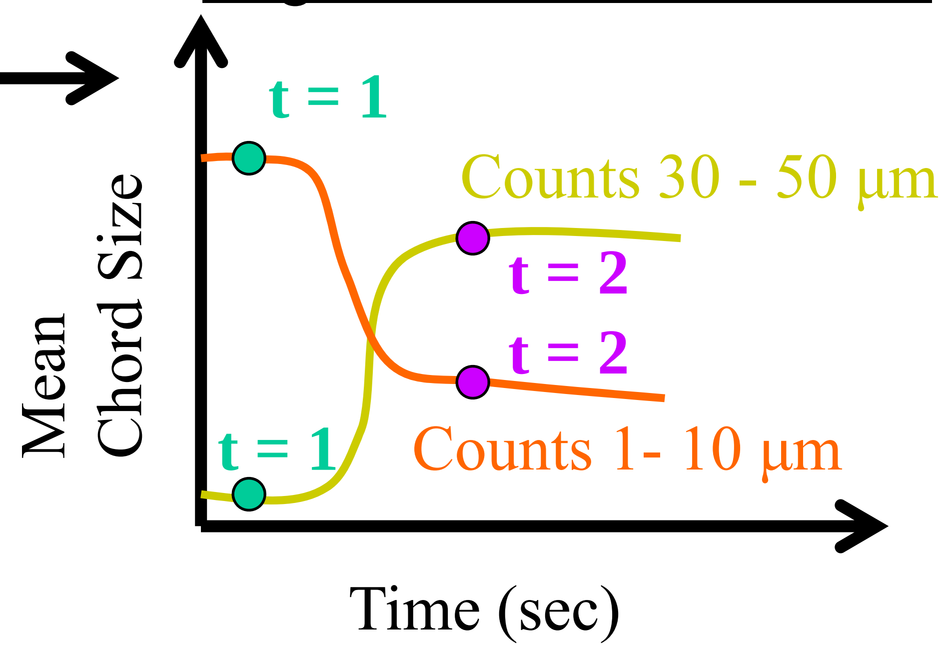
Sample Data



Statistics calculated from chord length distribution with time



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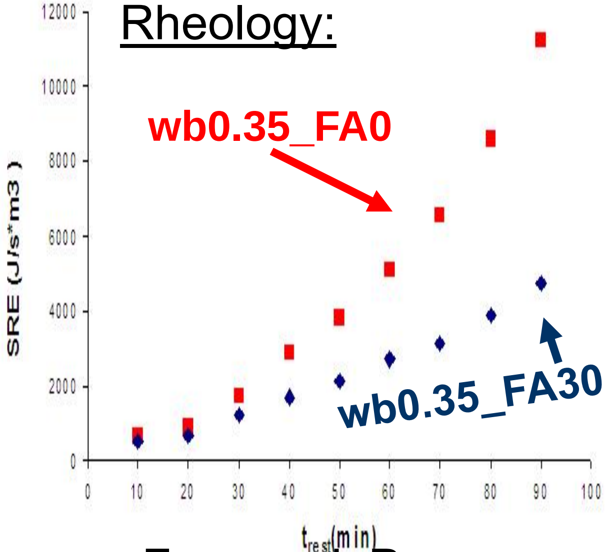
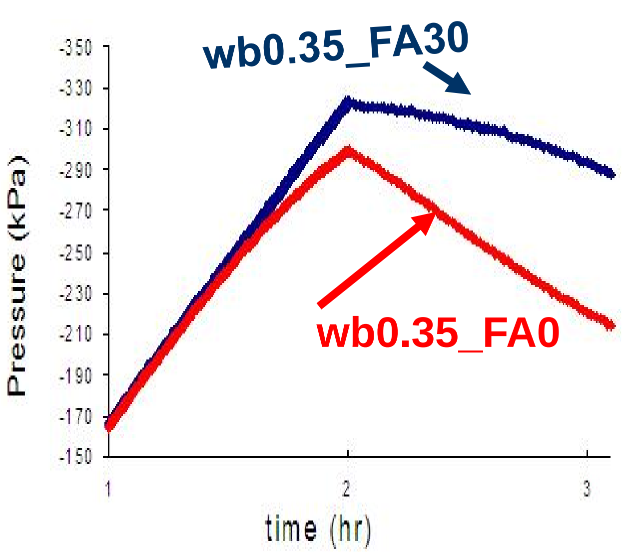
Linking Together Rheology, Formwork Pressure, and Flocculation

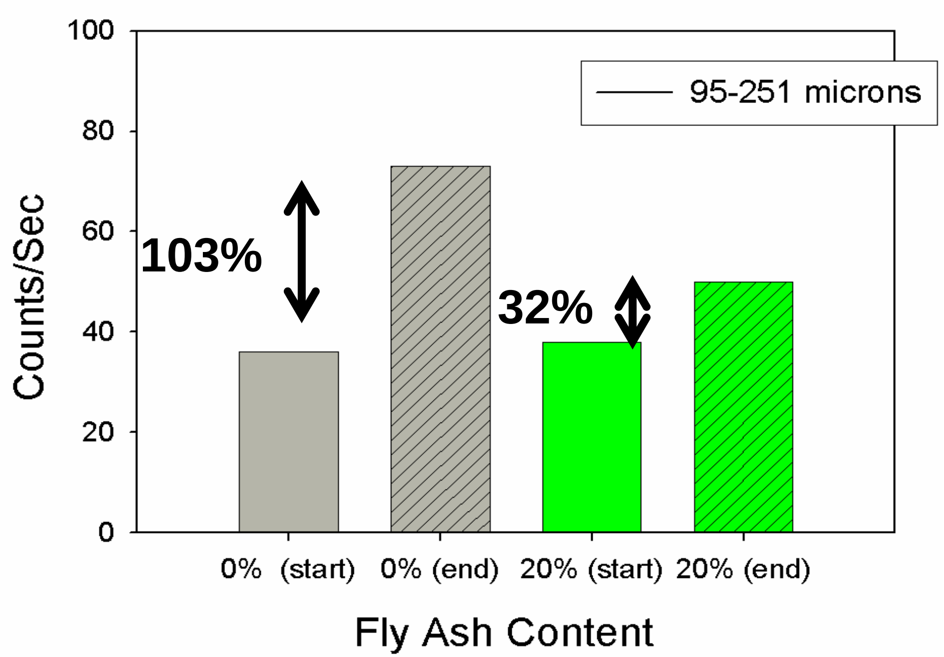
Rheology:



Formwork Pressure:

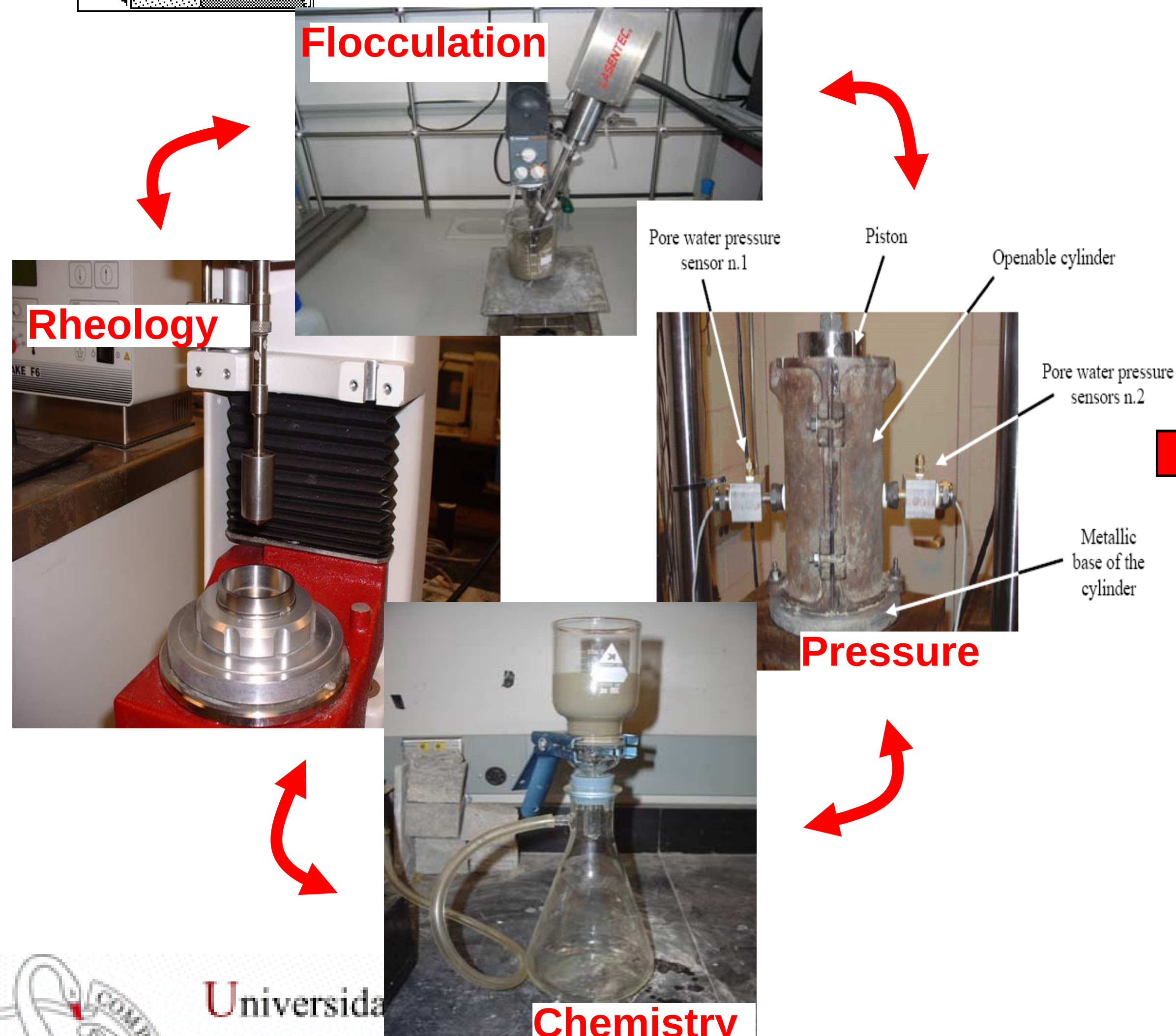


Number of counts at end of 30 minute buildup



Fly ash decreases flocculation

Linking Together



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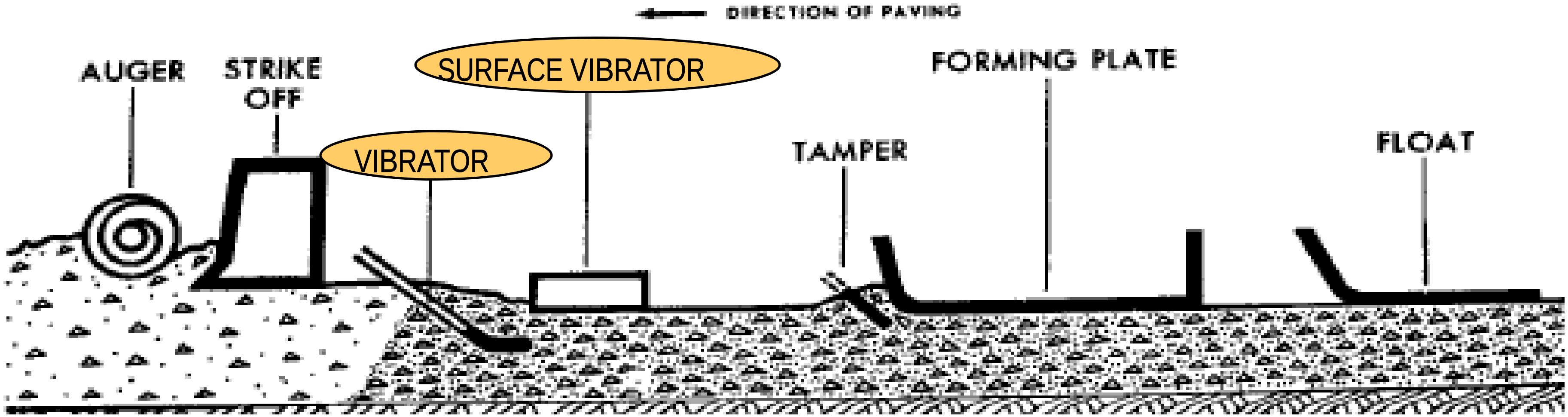
Applying SCC Technology to Slipform Pavements

Slipform Paving Process



Durability issues

- Slipform paving durability issues arise due to internal vibration (*loss of air content, segregation*)
- Eliminate need for internal vibration by manipulating the mix design…

Experimental Approach

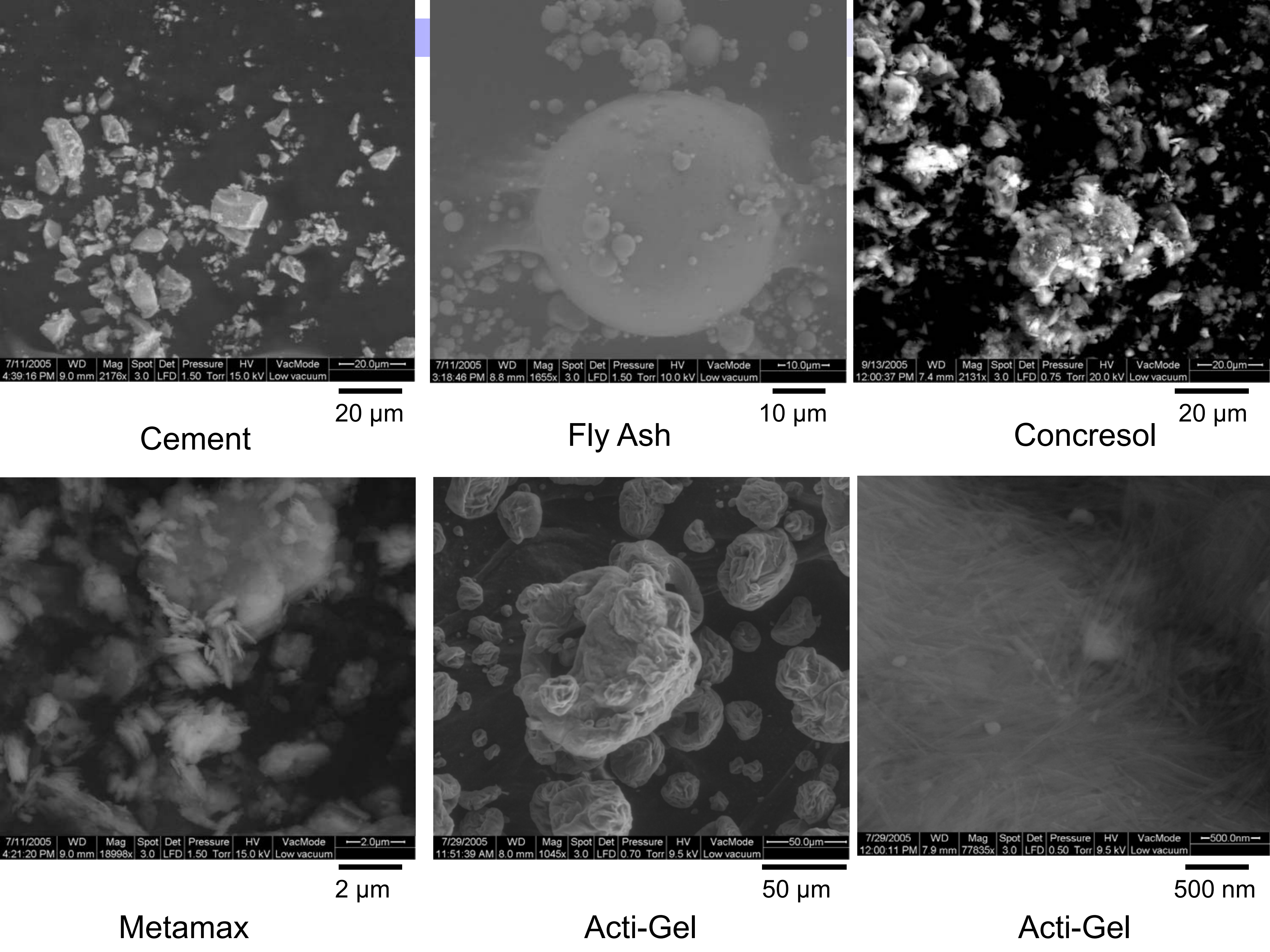
- Modification of conventional SCC until shape stable

Conventional SCC

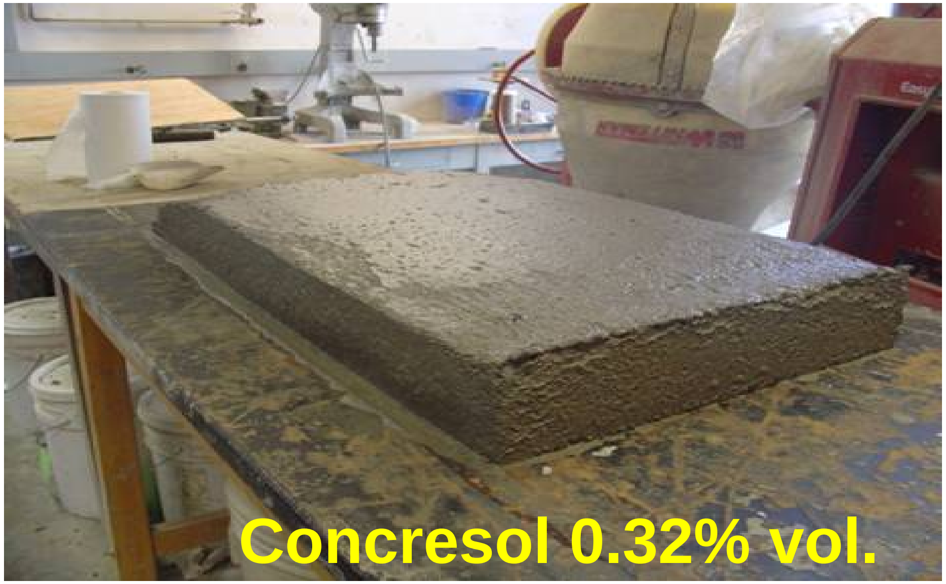
- Various Additives (clay, fly ash)
- Type and Amount of Plasticizer

Slipform SCC

Ultimate Goal: Eliminate Internal Vibration


7/11/2005 4:39:16 PM WD 9.0 mm Mag 2176x Spot 3.0 Det LFD Pressure 1.50 Torr HV 15.0 kV VacMode Low vacuum 20.0μm
20 μm
Cement
7/11/2005 3:18:46 PM WD 8.8 mm Mag 1655x Spot 3.0 Det LFD Pressure 1.50 Torr HV 10.0 kV VacMode Low vacuum 10.0μm
10 μm
Fly Ash
9/13/2005 12:00:37 PM WD 7.4 mm Mag 2131x Spot 3.0 Det LFD Pressure 0.75 Torr HV 20.0 kV VacMode Low vacuum 20.0μm
20 μm
Concresol
7/11/2005 4:21:20 PM WD 9.0 mm Mag 18998x Spot 3.0 Det LFD Pressure 1.50 Torr HV 15.0 kV VacMode Low vacuum 2.0μm
2 μm
Metamax
7/29/2005 11:51:39 AM WD 8.0 mm Mag 1045x Spot 3.0 Det LFD Pressure 0.70 Torr HV 9.5 kV VacMode Low vacuum 50.0μm
50 μm
Acti-Gel
7/29/2005 12:00:11 PM WD 7.9 mm Mag 77835x Spot 3.0 Det LFD Pressure 0.50 Torr HV 9.5 kV VacMode Low vacuum 500.0nm
500 nm
Acti-Gel

Effect of Materials on Shape and Surface

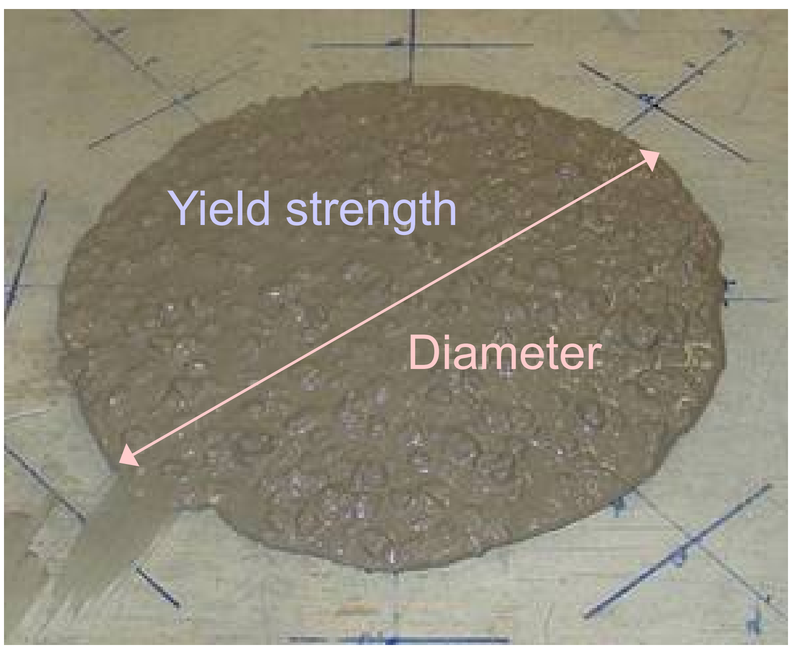


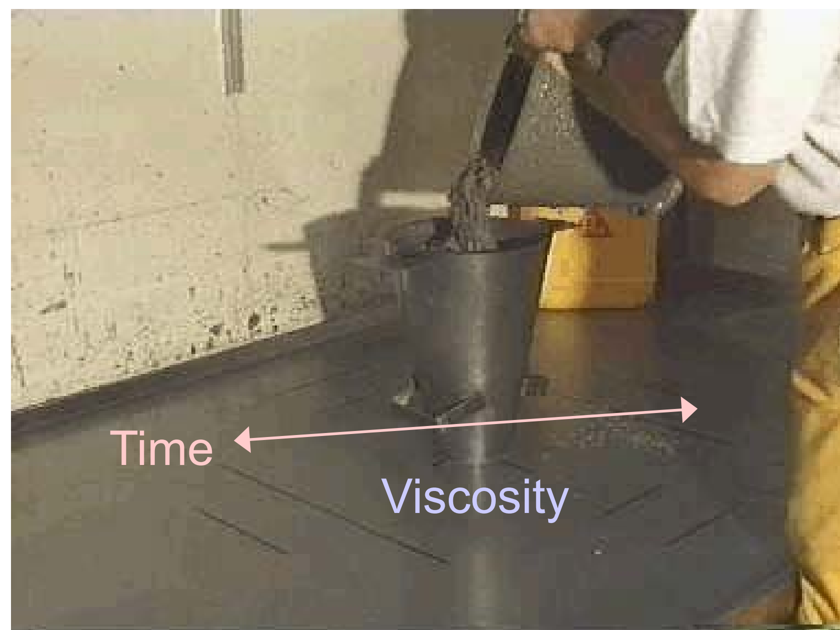
How Does Clay Affect Flocculation?

- Methods of investigation:
  - Shear rheology
  - Compressive rheology
  - Floc size determination

From Lab to Practice

- Relating fundamental properties to common slump or flow tests
  - Final spread ⇨ yield strength?
  - Time to final spread ⇨ viscosity?



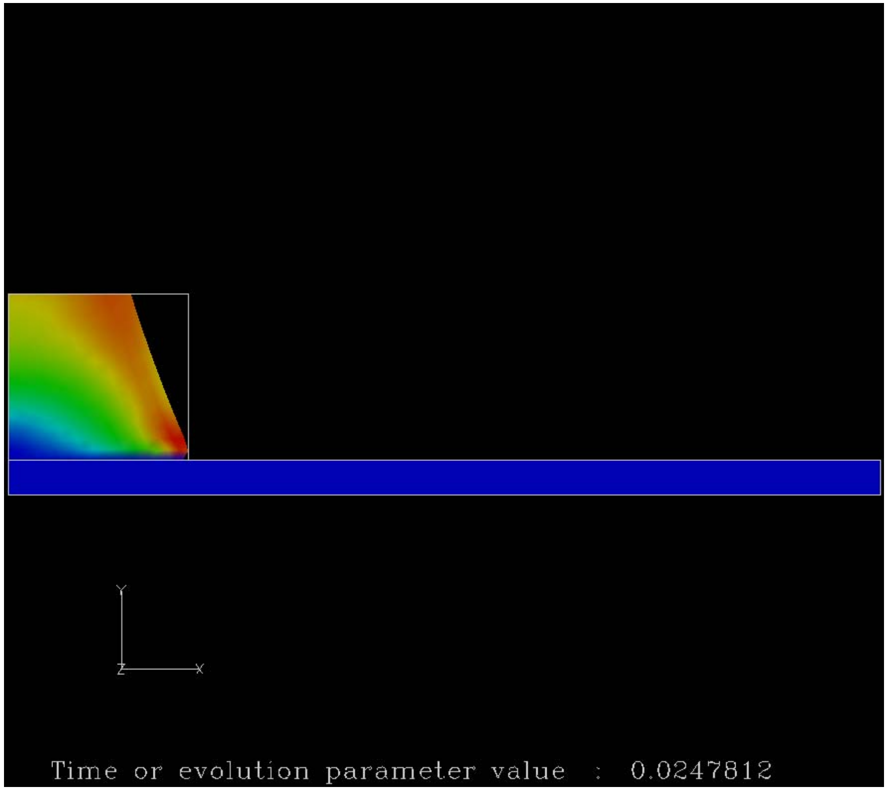


Experimental Setup

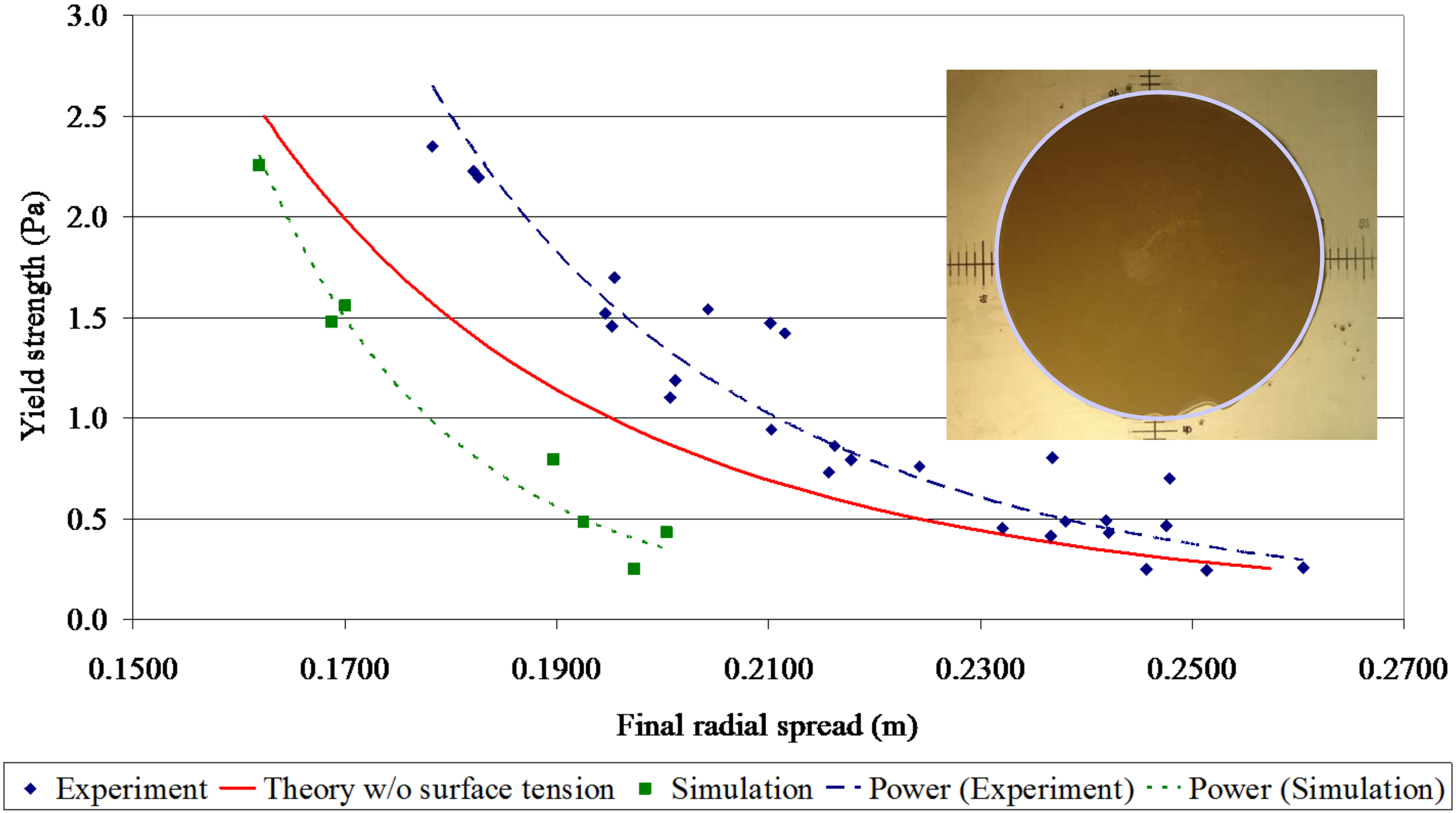
- Measuring final diameter and time it takes to reach a given diameter for cement paste

Modeling Setup

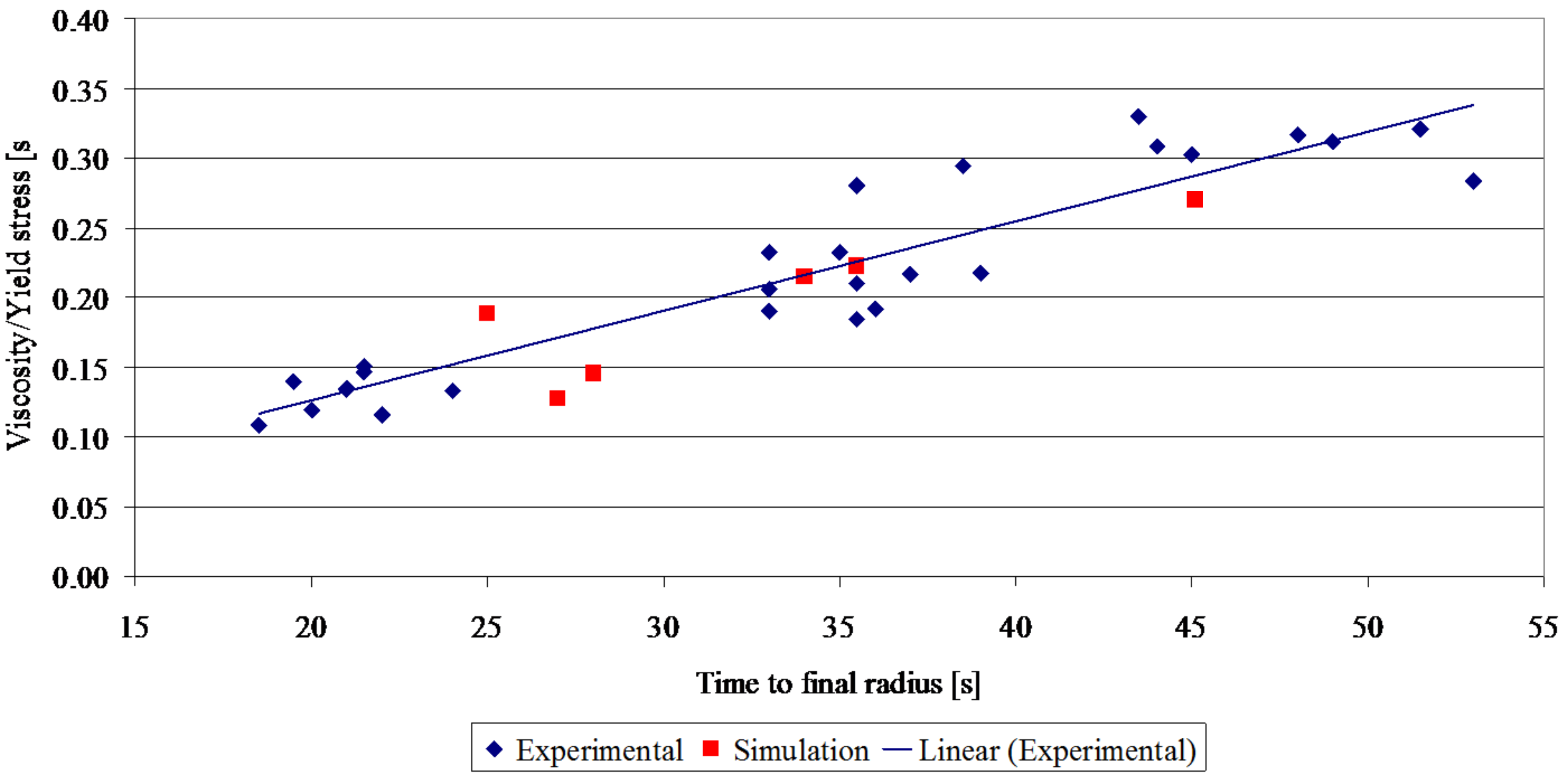
- Using Fluent's POLYFLOW to numerically simulate the flow of cement paste



Yield Strength – Final Spread Relationship



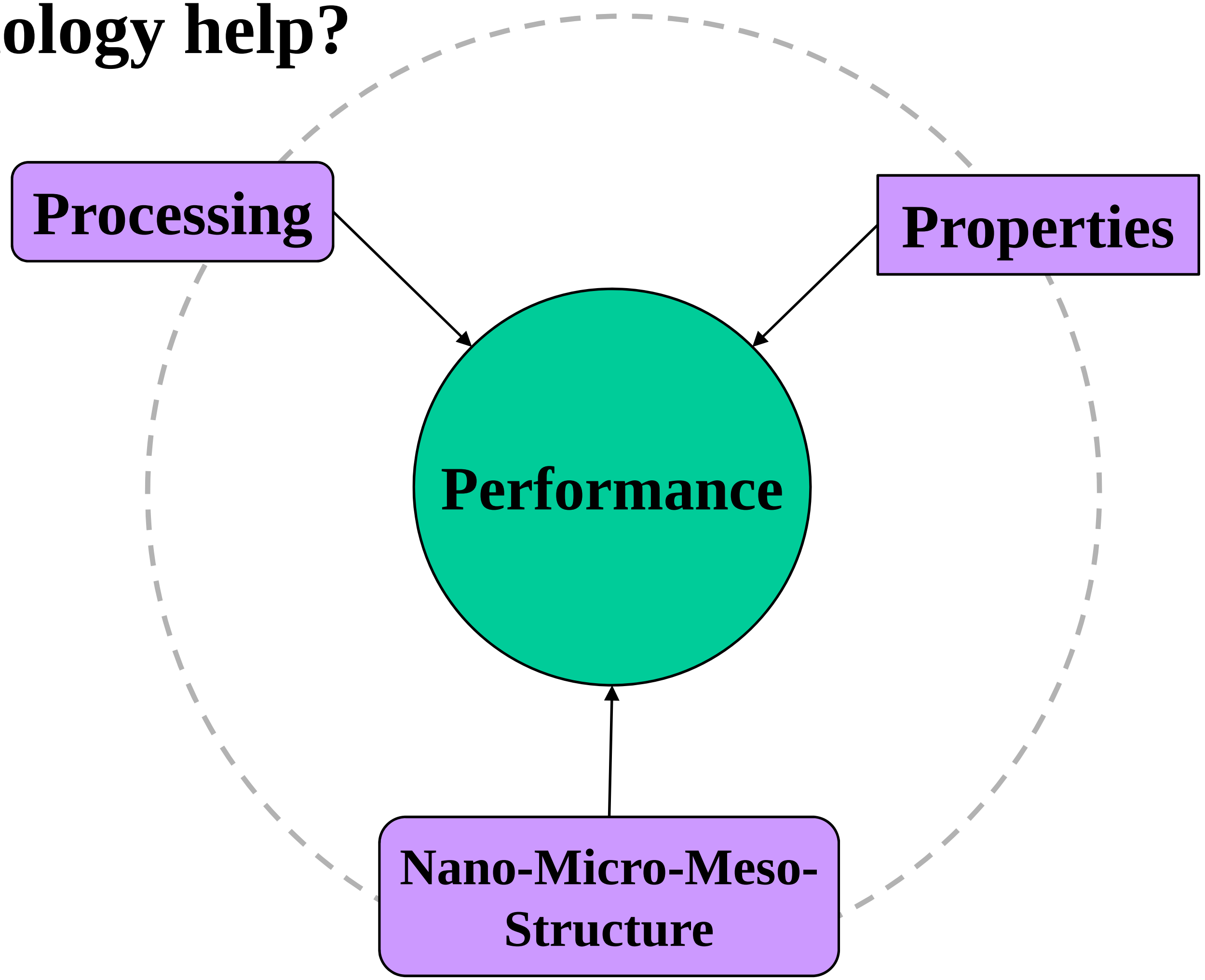
Viscosity / Yield Stress – Final Time Relationship



Nanomodification of Cementitious Materials

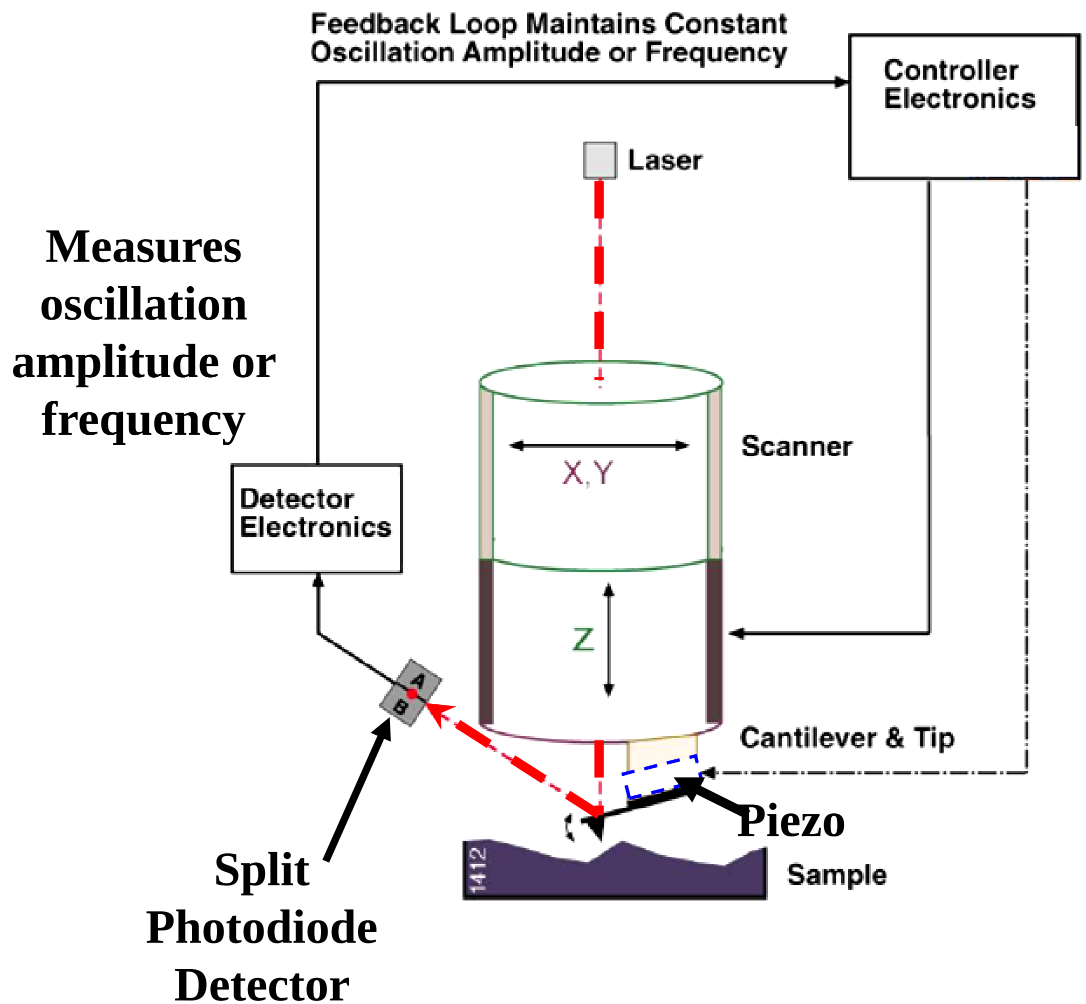
How can Nanotechnology help?

- Characterization
- New materials
- Sensors

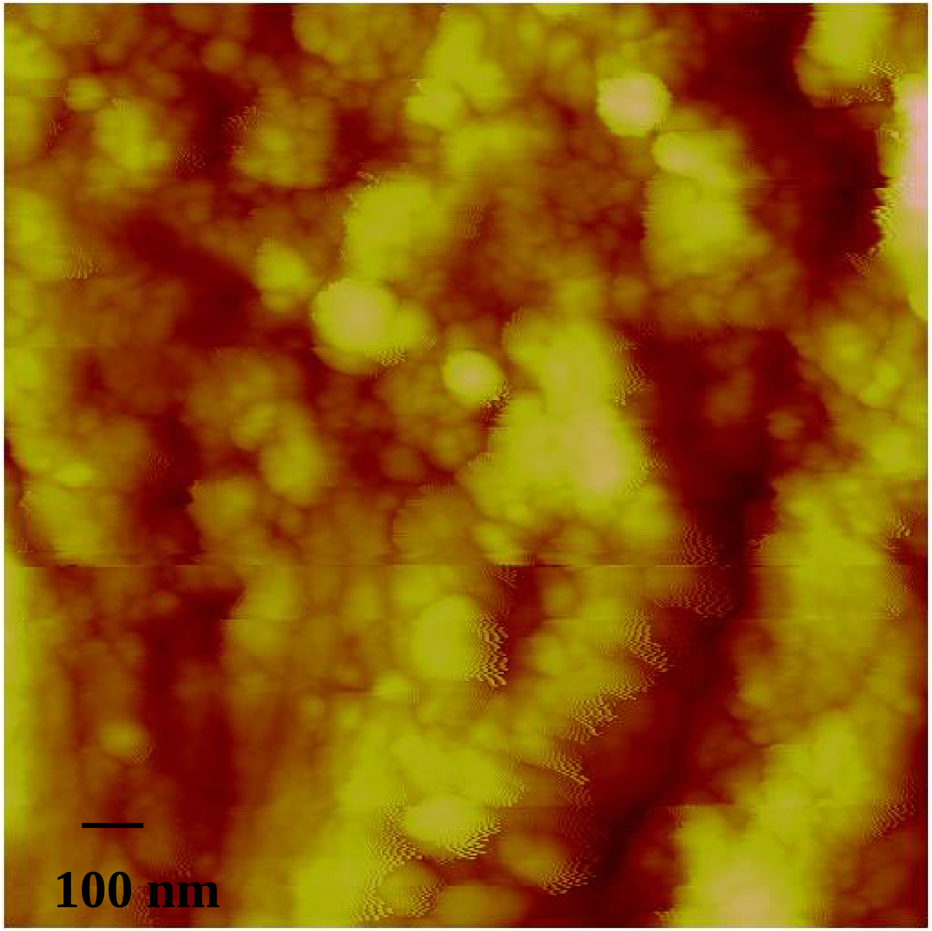


Atomic Force Microscopy

- Images sample surface at nano-scale
- Abilities:
  - Normal atmospheric temperature and pressure
  - Under liquid
  - Determines mechanical properties (Young’s modulus) in conjunction with imaging



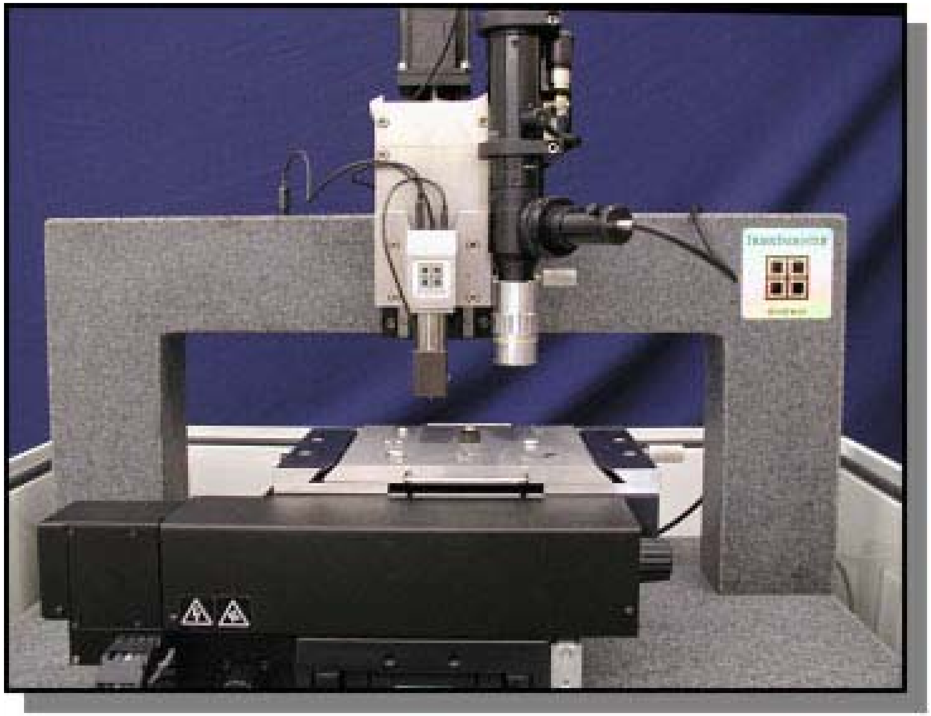
Atomic Force Microscopy Image of Calcium Silicate Hydrate (C-S-H)

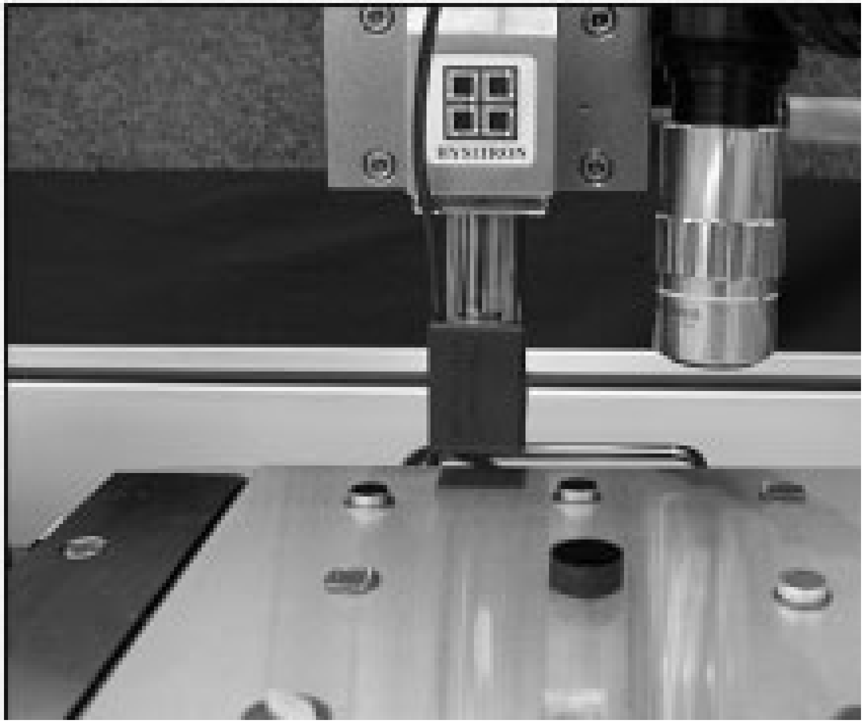


- Image size: 1.5 μm x 1.5 μm, spherical particles of the order of 40 nm
- Maximum height difference between different points ~ 0.3 μm

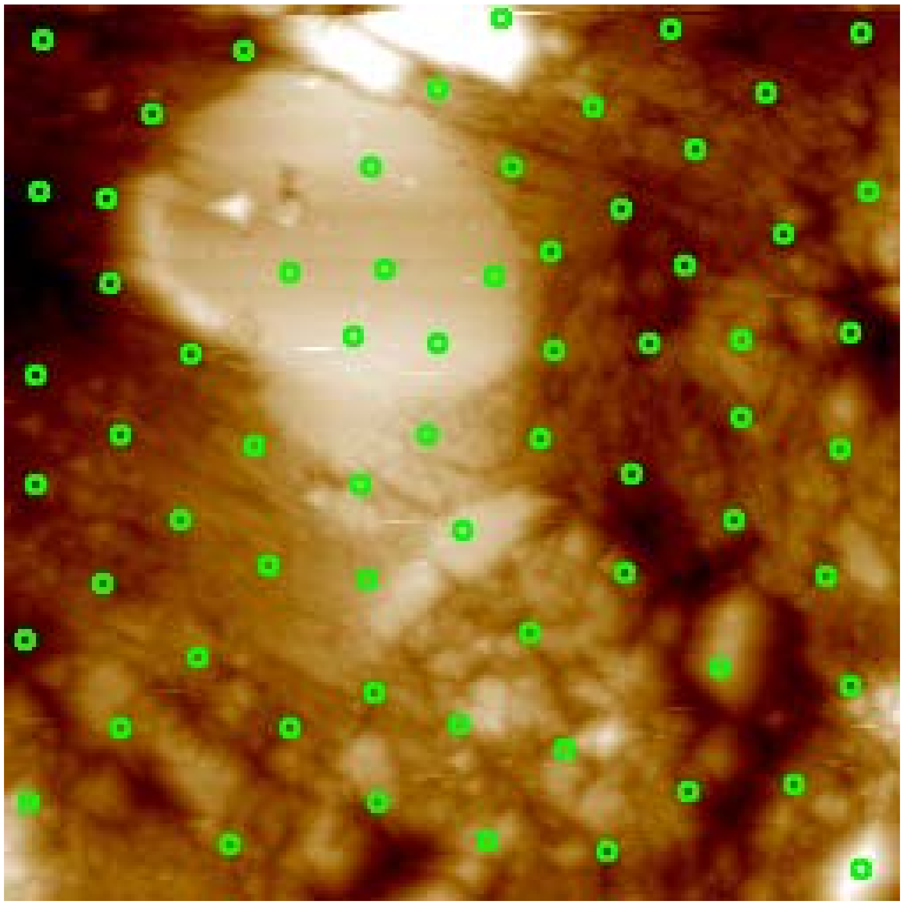
Hysitron Triboindenter

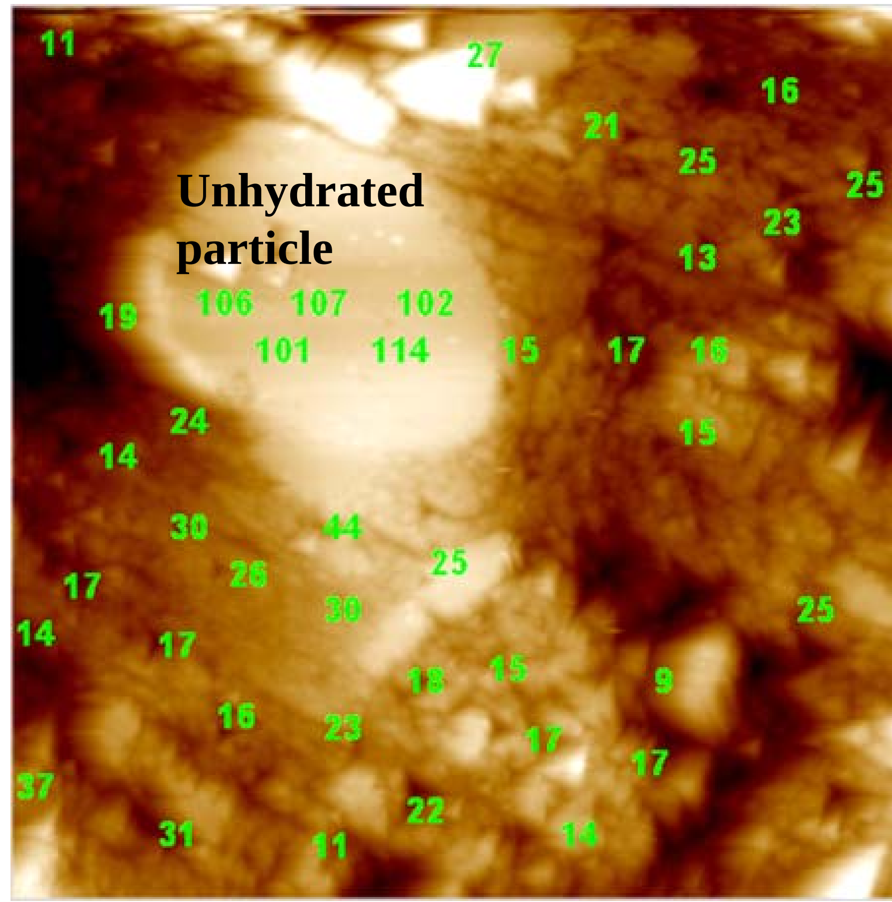
- Can do both nanoindentation and scanning probe microscopy imaging
- Berkovich tip has been used





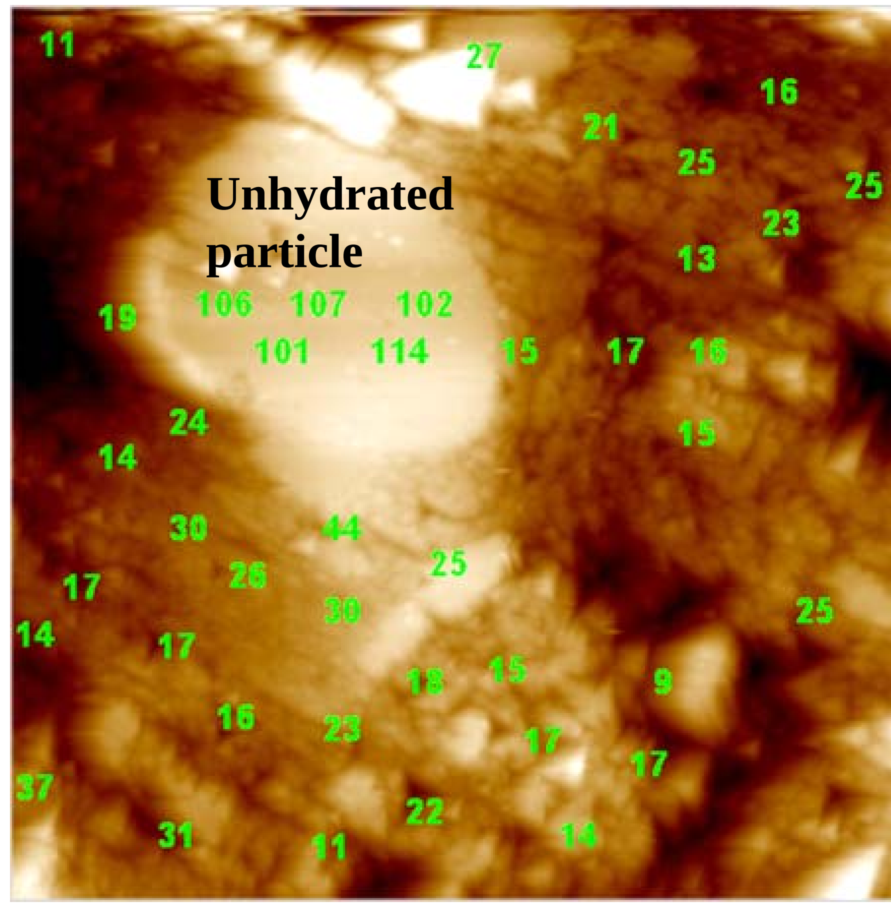
Nanoindentation on 6 Months Old Cement Paste: w/c 0.5





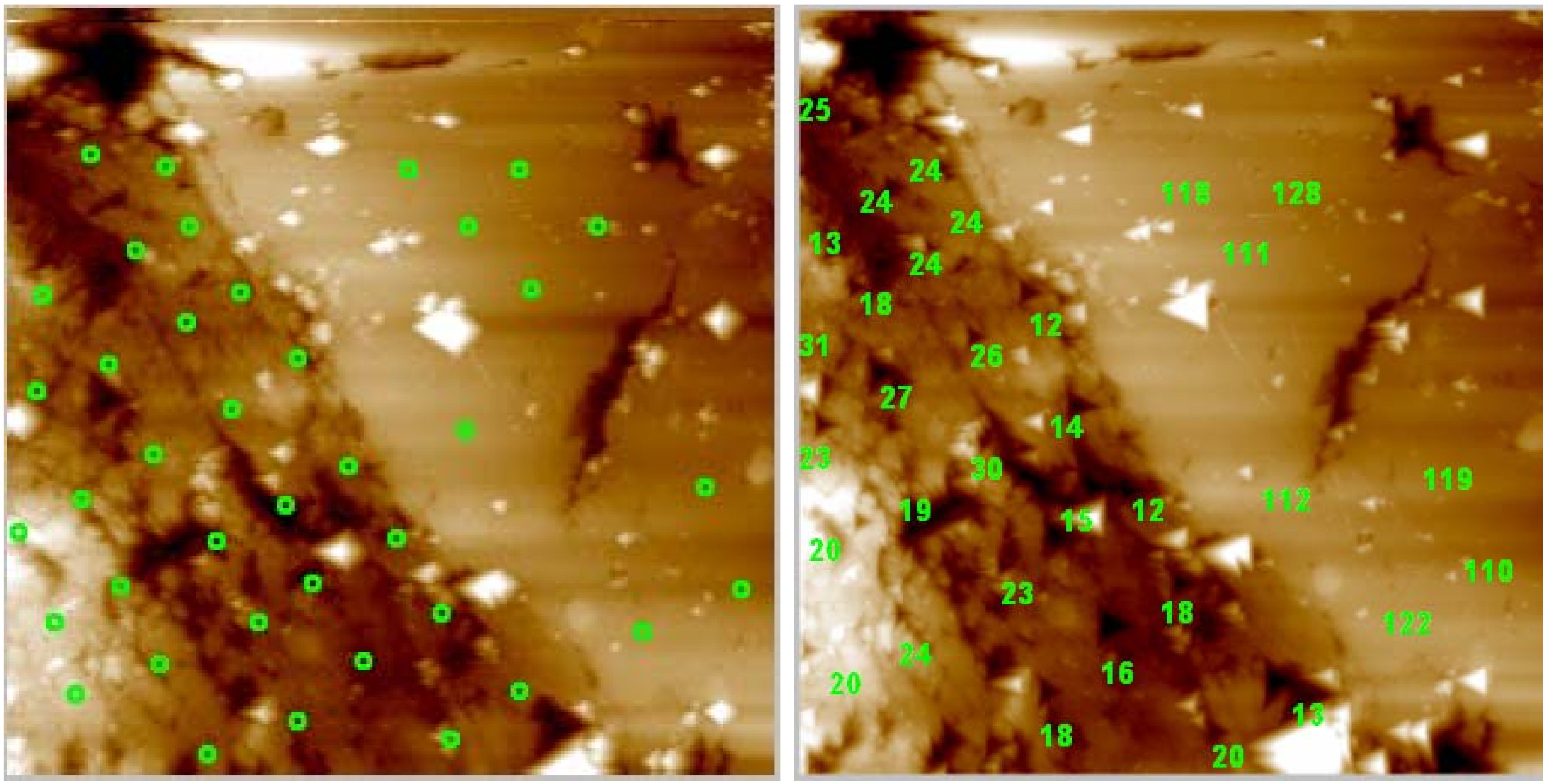
- Image size: 60 μm x 60 μm
- Left image shows indent locations, right image shows Young's Modulus in GPa

Nanoindentation on 6 Months Old Cement Paste: w/c 0.5



- ➢ **Image size: 60 μm x 60 μm**
- ➢ **Left image shows indent locations, right image shows Young's Modulus in GPa**

Nanoindentation on Sand, ITZ and Paste Matrix



- Image size: 60 μm x 60 μm
- Left image shows indent locations, right image shows Young's Modulus in GPa

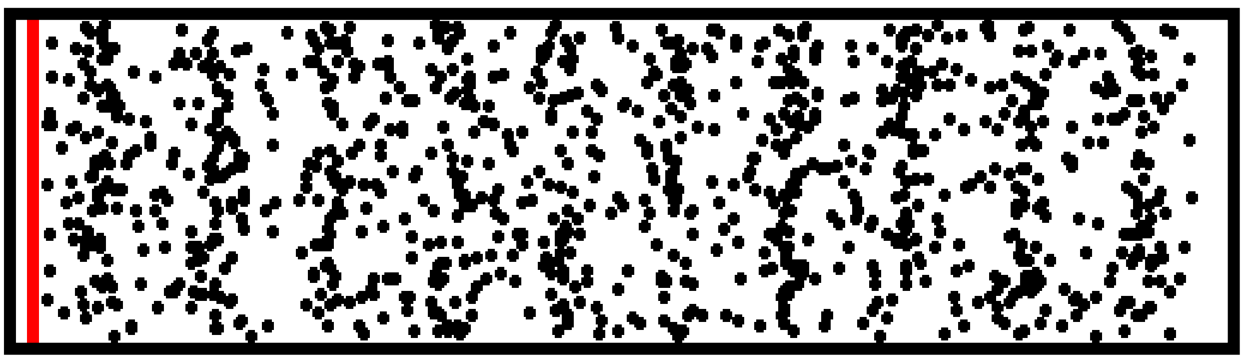
Sensors

- Impedance Spectroscopy
- Ultrasonic Sensing System
- Nuclear Magnetic Resonance
- Dielectric Measurements with Microwaves

Ultrasonic Sensing: Early Age Monitoring with Wave Reflection

Longitudinal waves (L-waves) [also: Primary (P-) Waves, Compression Waves]

Excitation



Direction of Travel

Direction of Particle Motion

Wave Velocity:

$$v_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$$

<u>Governing Parameters</u>

Young's Modulus E

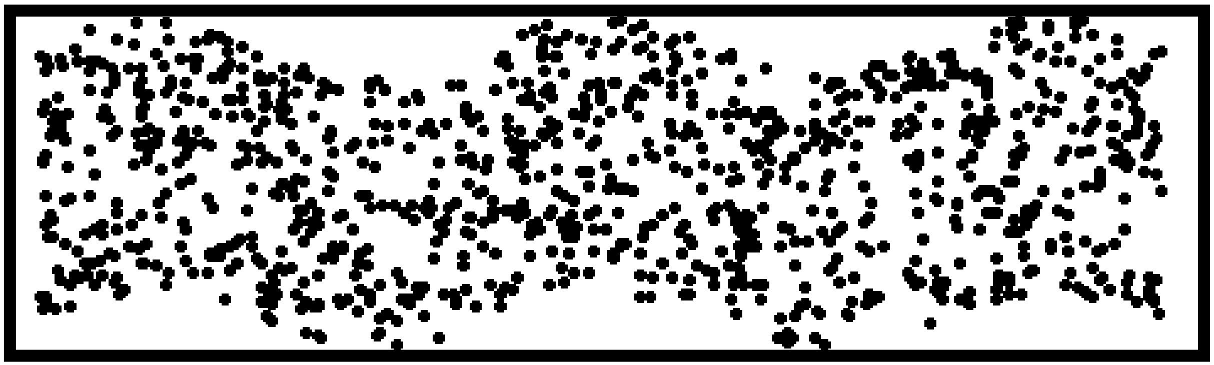
Poisson's Ratio ν

Density ρ

Transverse Waves (T-waves)

also: Secondary (S-) Waves, Shear Waves

Excitation



Direction of Travel

Direction of Particle Motion

Wave Velocity:

$$v_T = \sqrt{\frac{G}{\rho}}$$

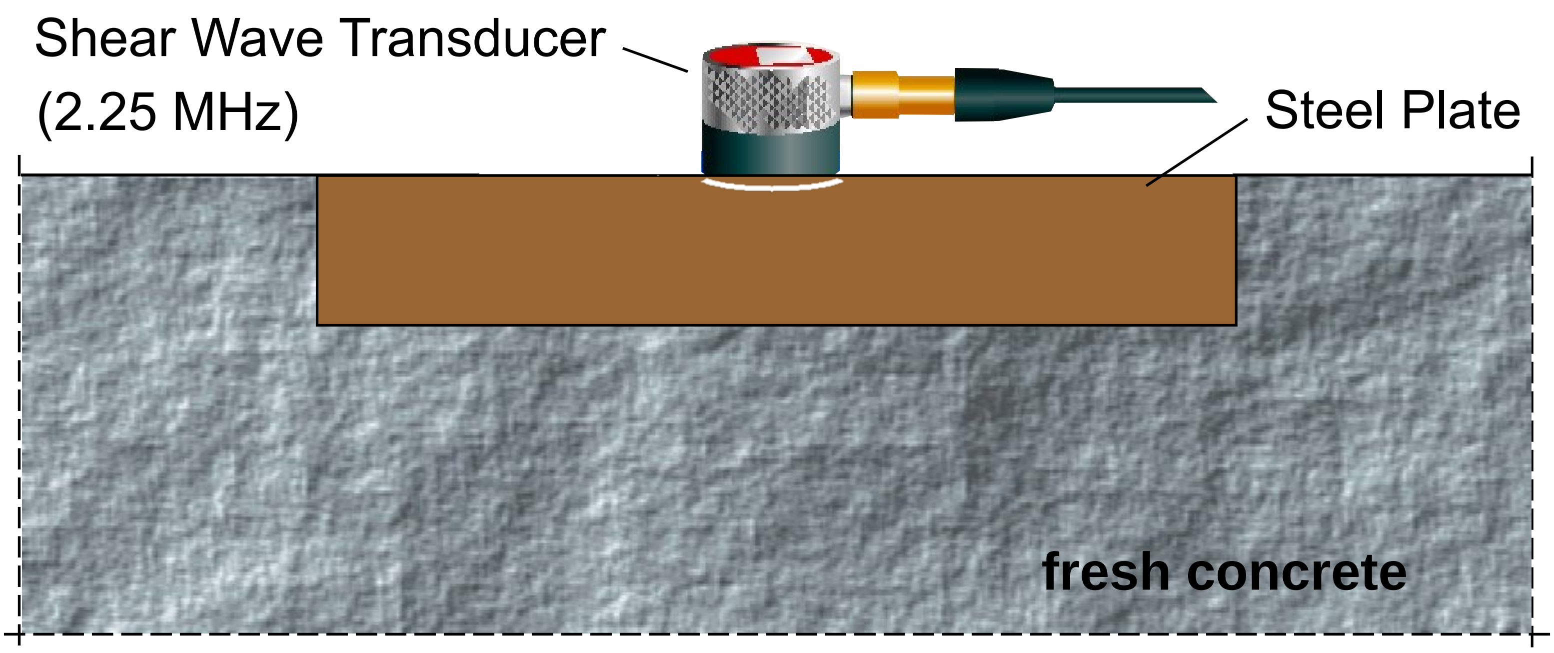
<u>Governing Parameters</u>

Shear Modulus G

Density ρ

no propagation in liquids or gases !

Principle of Wave Reflection Method

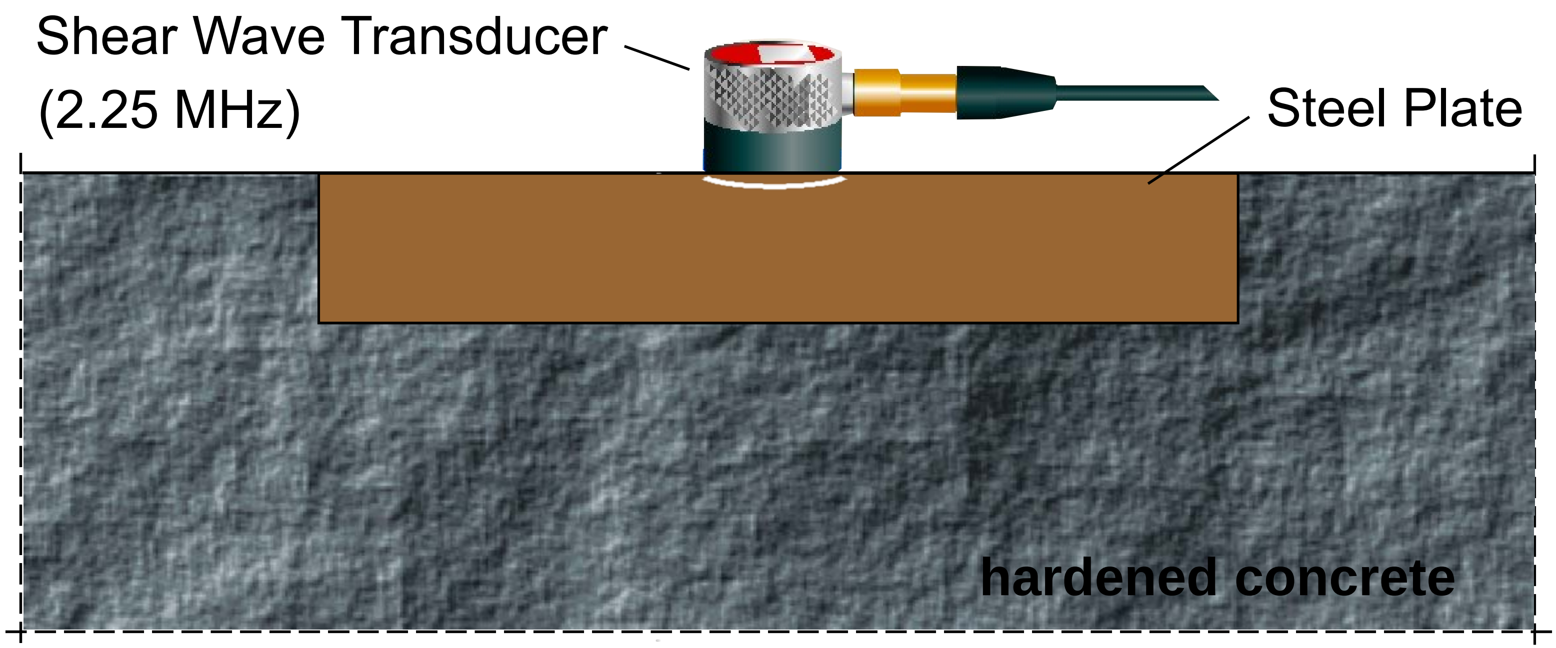


Case 1: concrete is liquid

No wave transmission at interface

Shear waves: do not propagate in liquids

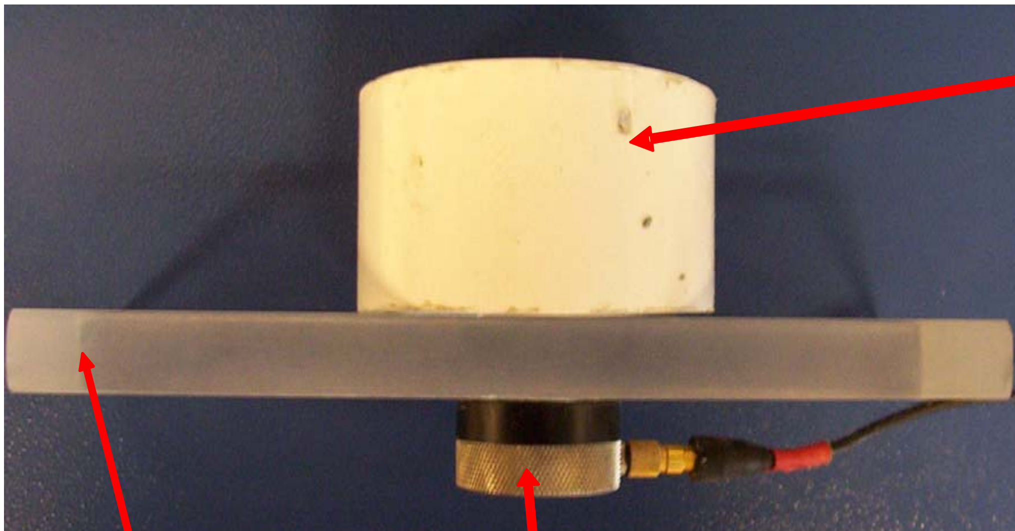
Principle of Wave Reflection Method



Case 2: concrete is hardening

Transmission losses at interface

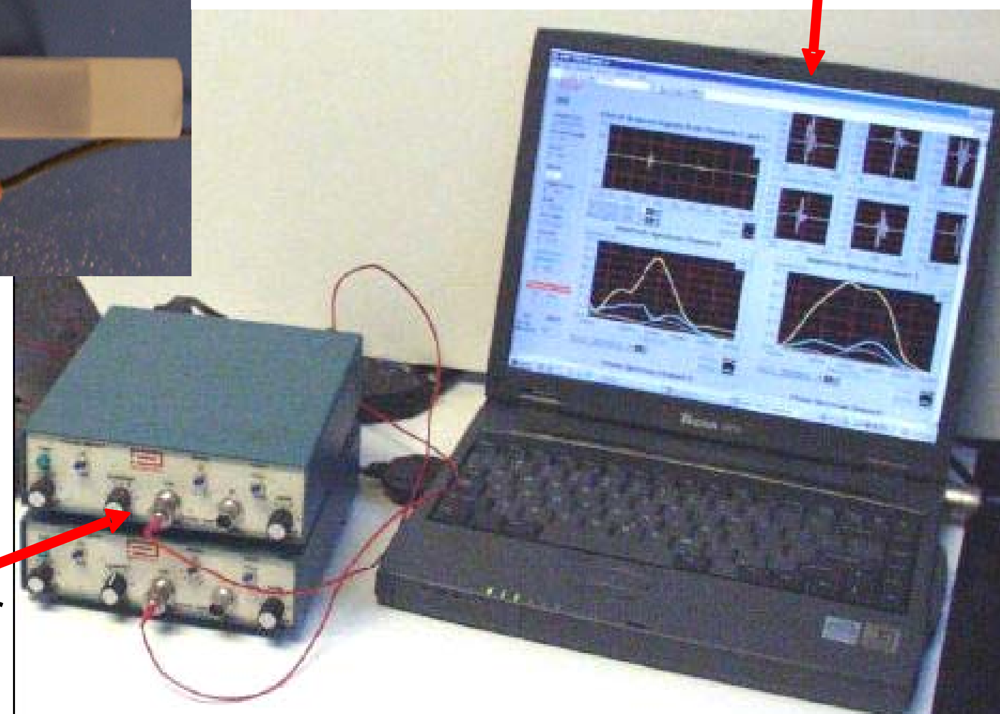
Ultrasonic Sensing: Experimental Setup



Fresh

cement paste

Computer



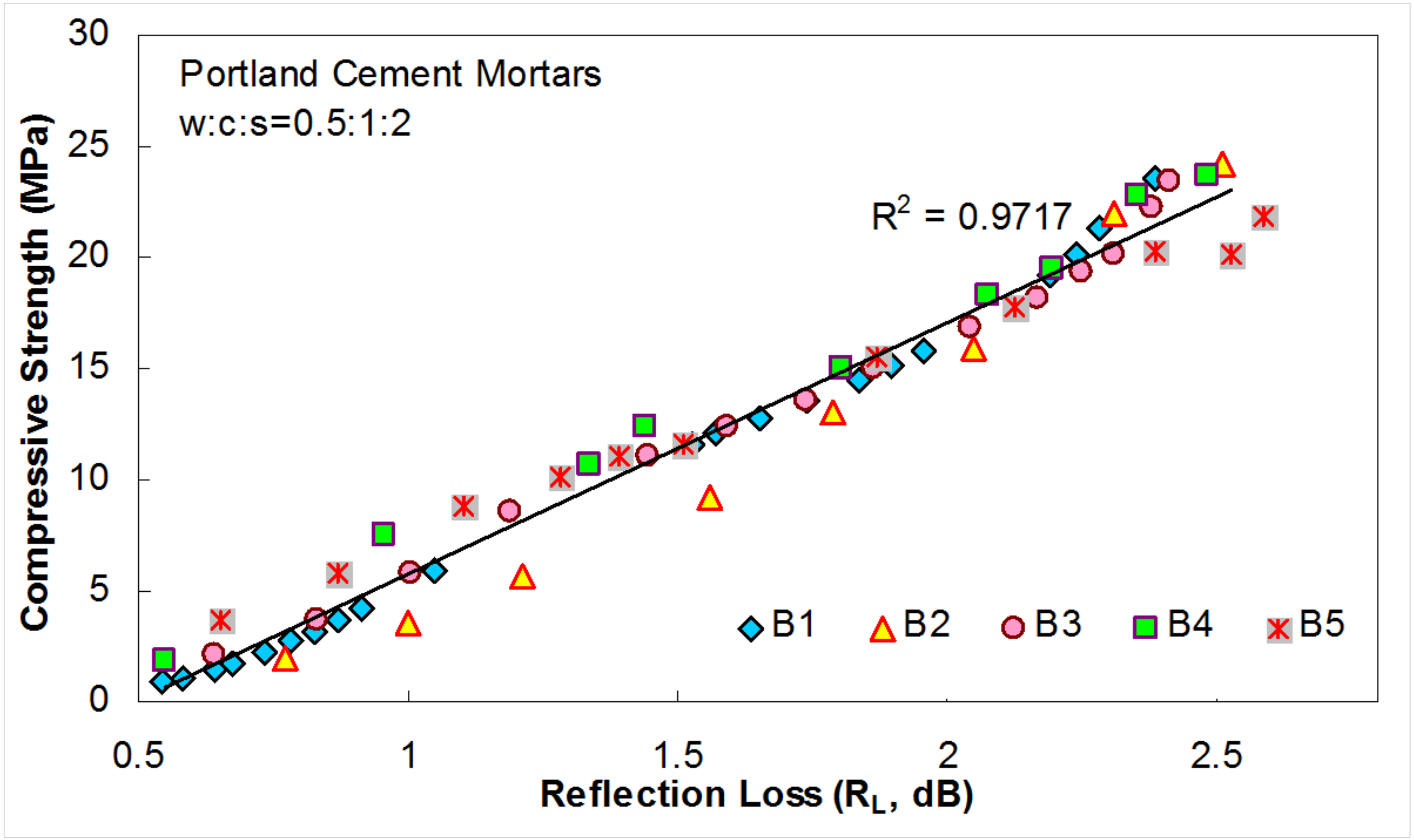
Buffer material

Transducer (2.25MHz)

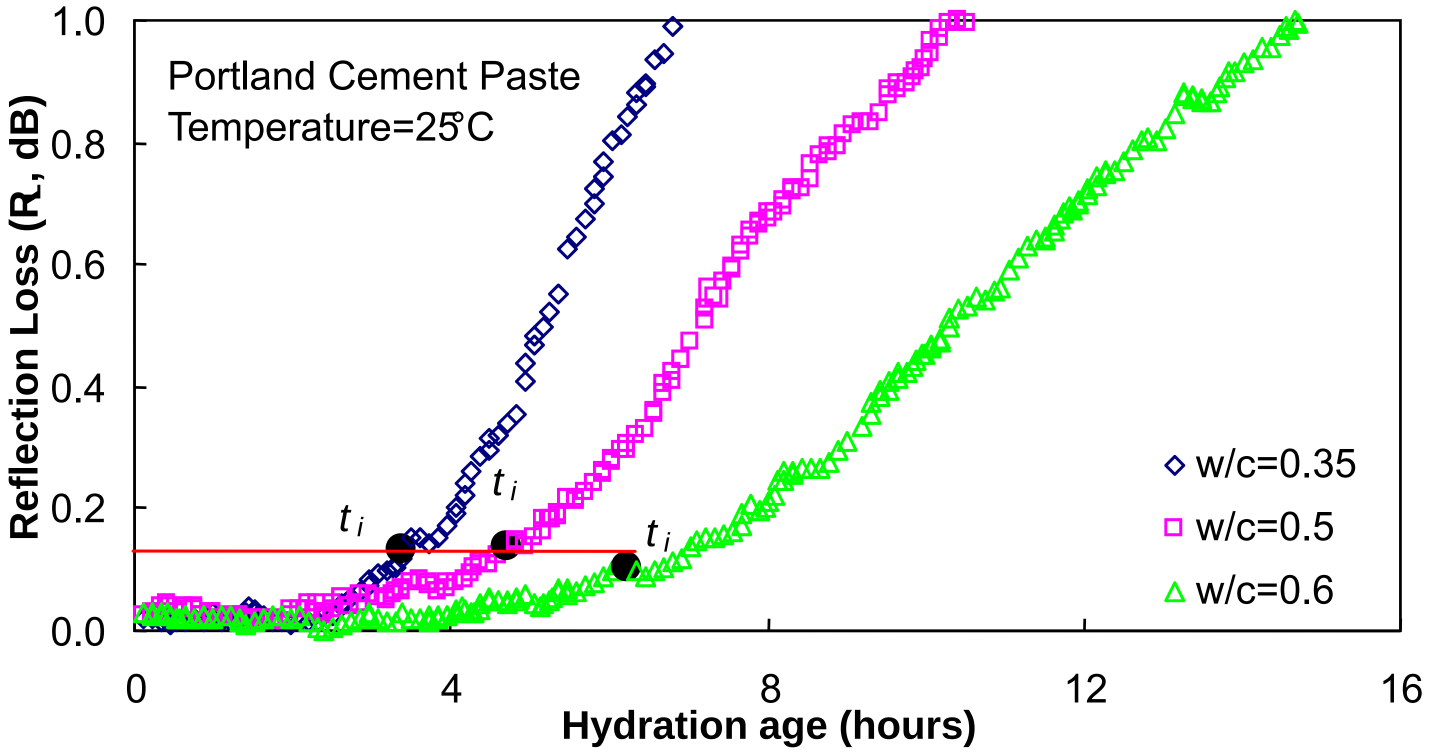
Wavelength: ~0.1-1μm
at early ages

Pulser

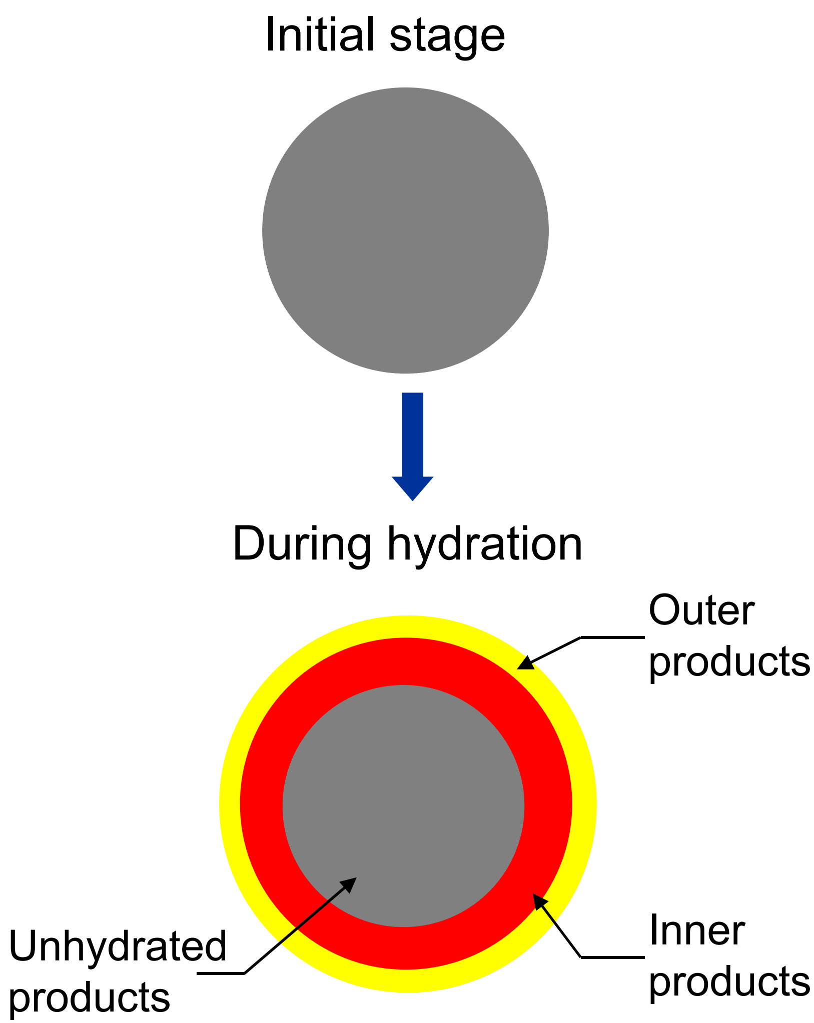
Compressive Strength Correlation with Reflection Loss

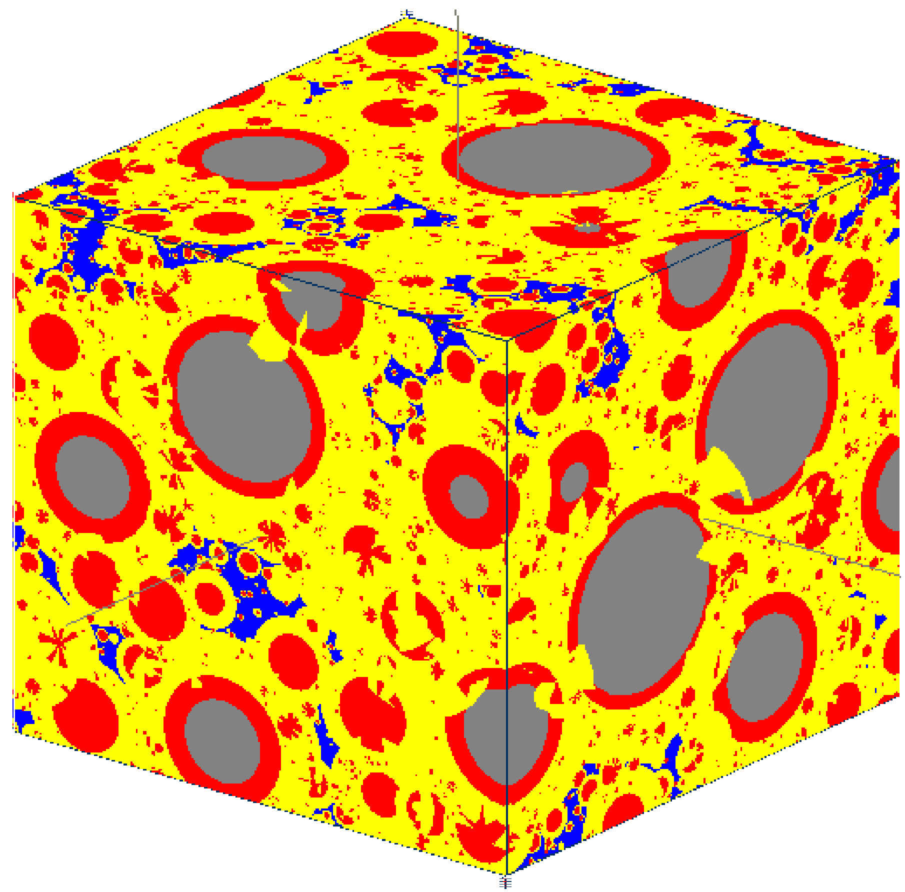


Reflection Loss and Initial Setting Time

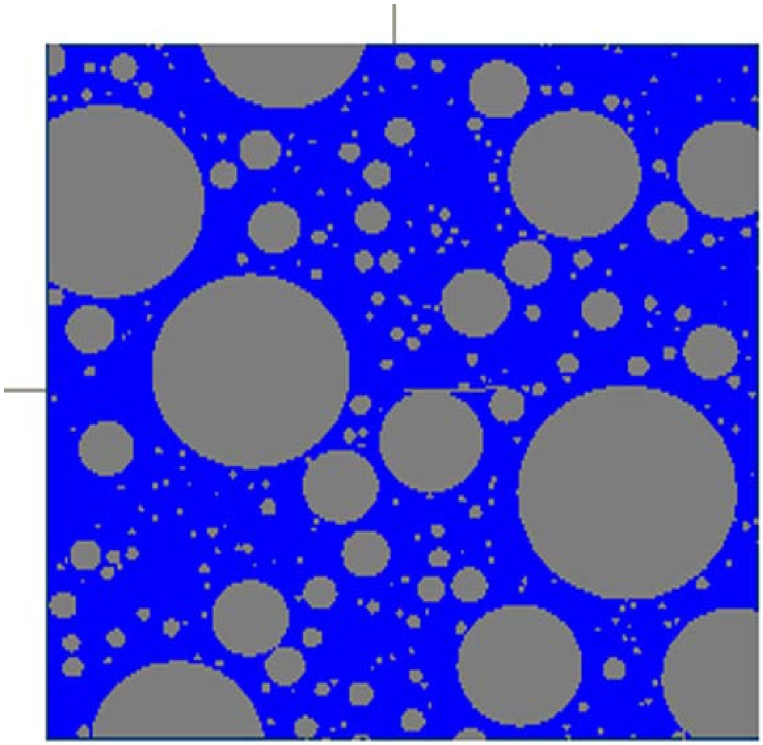


How Can R_L be Related to Microstructural Changes?

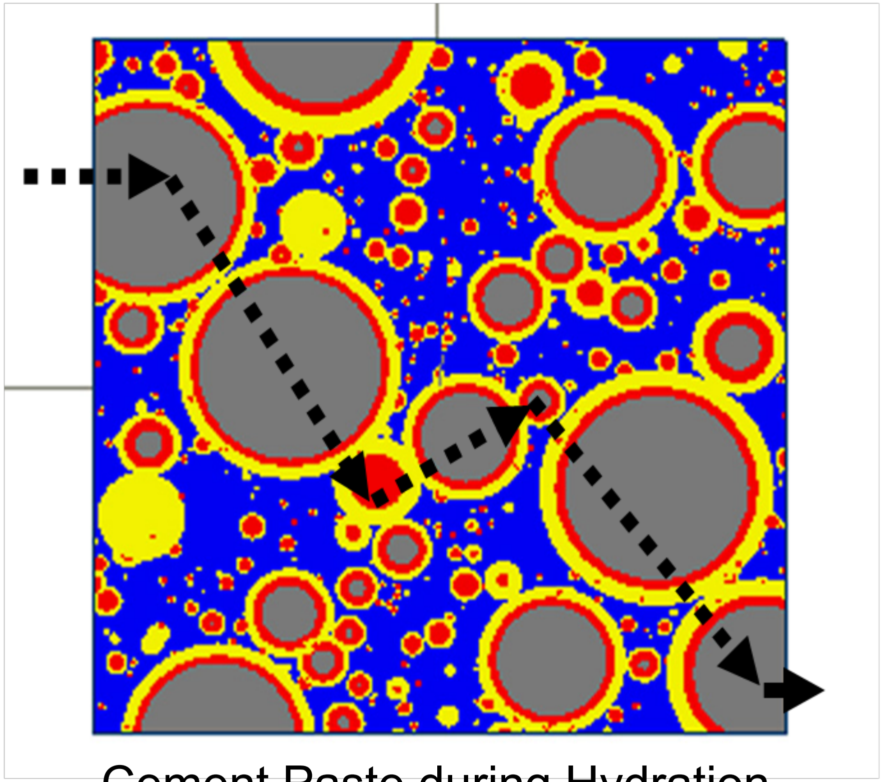




Percolation of Solid Phase



Original Cement Paste



Cement Paste during Hydration

New Materials: Photocatalysis

- A new and innovative approach shows that photocatalytic activity may be conferred to cementitious construction materials such as paints, mortars, concrete, roads etc.
- TiO_2 is effective in reducing pollutants such as NO_x, aromatics, ammonia, and aldehydes
- TiO_2 in combination with cementitious materials has shown a favorable synergistic effect in the reduction of pollutants

L. Cassar, CTG Italcementi Group, Italy

2nd International Symposium on Nanotechnology in Construction, Nov 2005, Bilbao, Spain

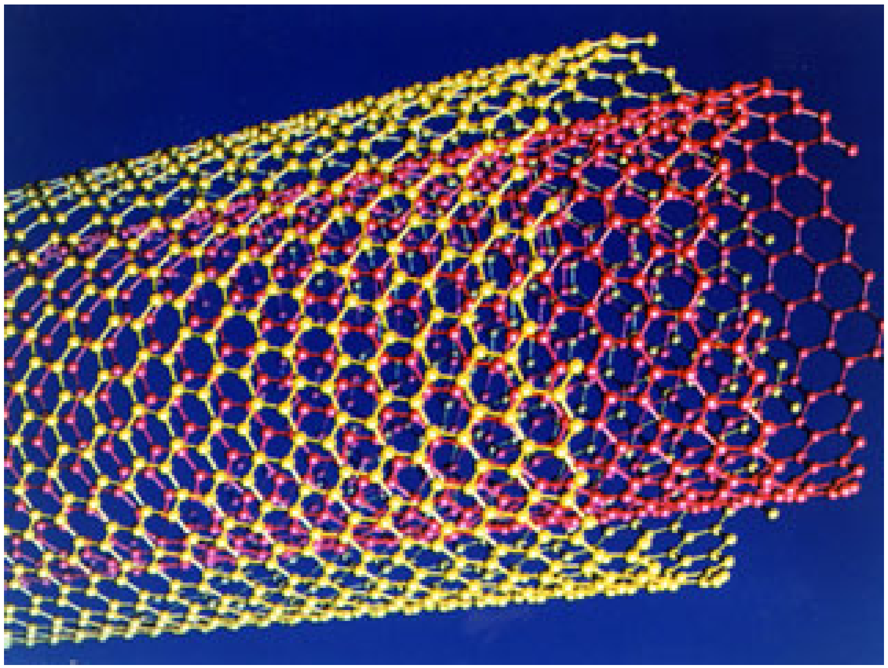
Photocatalysis in Cementitious Materials

- BiancoTX Millennium white cement incorporating titanium dioxide was used for the “Dives in Misericordia” church

CTG Italcementi Group, Italy

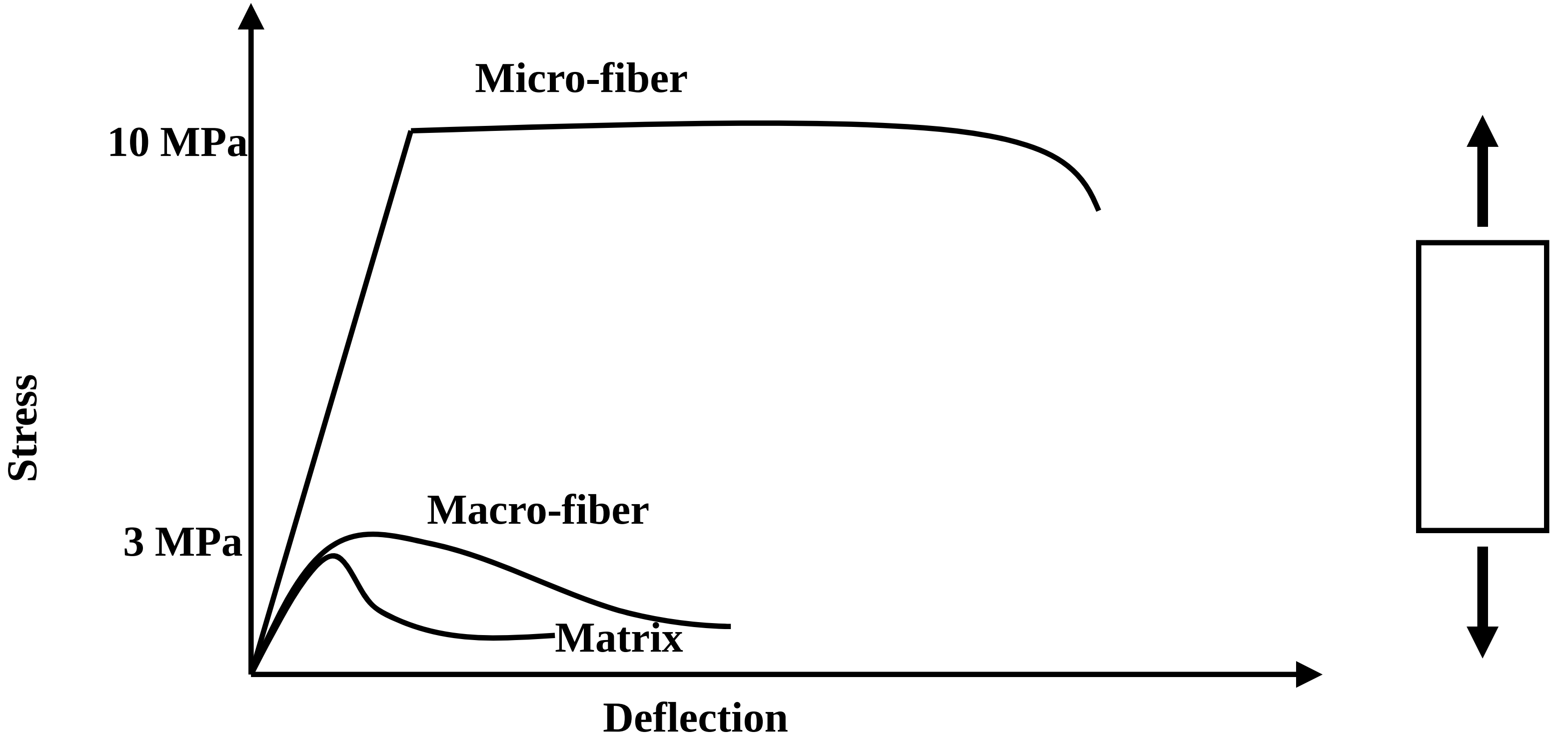
New Materials: Carbon Nanotubes

- **Extremely high tensile strengths**



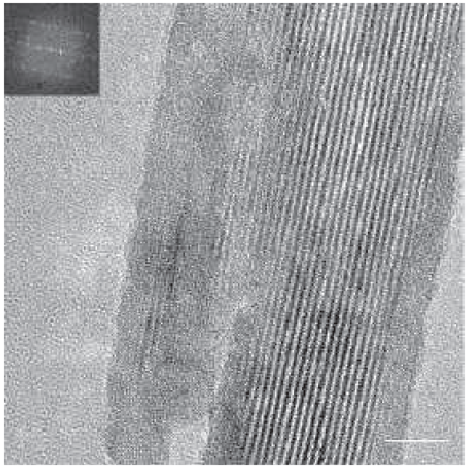
Nanotechnology and FRC

- Can we achieve superplasticity by modifying at nanoscale?



New (Old?) Materials!

- Damascus sabers contain *carbon nanotubes*, as well as *nanoscale wires of cementite*, giving them a moiré pattern (from Nov. 28 article in NY Times, photo taken by Tina Fineberg)
- Nanotubes over 400 years old!



TEM image showing nanotubes
[Reibold et. al, 2006]

Thank you!

Acknowledgements

National Science Foundation
WHERE DISCOVERIES BEGIN

U.S. Department of Transportation
Federal Highway Administration

NRMCA NATIONAL READY MIXED CONCRETE ASSOCIATION

SDC The Concrete Industry's Strategic Development Council

Universidad Complutense Madrid

NORTHWESTERN UNIVERSITY
INFRASTRUCTURE TECHNOLOGY INSTITUTE